DESIGN OF AN ADAPTIVE FUZZY ESTIMATOR FOR FORCE/POSITION TRACKING IN ROBOT MANIPULATORS

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Abstract. This paper presents a stable new algorithm for force/position control in robot manipulators. In this algorithm, position vectors are measured by sensors and then used in the control law. Since using force sensor has some issues such as high costs and technical problems, an approach is presented to overcome these issues. In this respect, force sensor is replaced by an adaptive fuzzy estimator to estimate the external force based on position and velocity measurements. In this approach, force can be properly estimated using universal approximation property of fuzzy systems. Therefore, robots can be controlled in different environments even when no exact mathematical model is available. Since this approach is adaptive, accuracy of the system can be improved with time. Through a theorem the stability of the control system is analyzed using Lyapunov direct method. At last, satisfactory performances of the proposed approach are verified via some numerical simulations and the results are compared with some previous approaches.

1. Introduction

In some robotic applications, robot arm is in contact with environment and environmental forces are exerted on the robot. On the contrary, in some others, the robot exerts external forces to the environment. As an illustration, in some applications such as deburring, grinding and precise assembly it is necessary that end effecter contacts with environment and maintains this contact [10], and in robotic assembly for electronic components, success highly depends on ability to monitor and control the insertion force.

Generally, there are two main proposes for handling force in a control system. In some applications, the force is considered as an external disturbance from environment to robot and force disturbance cancellation is the aim because the external force disturbance can highly influence the system performance. For instance, exerting on unexpected force on a mobile manipulator can make the robot motion unstable [12]. To achieve suitable performance in such cases, both force and position must be considered in control system design. In other applications, a desired force must be exerted on the environment by robot arm and at the same time the desired trajectory must be tracked properly. In this type of control system two

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broad approaches are reported in the literature for robot control in constrained motions: impedance control and hybrid (force/position) control [14].

In impedance control, a prescribed static or dynamic relation is sought to be maintained between the robot end effector force and position. In hybrid control, the end effector force is explicitly controlled in selected directions and the end effector position is controlled in the remaining (complementary) directions [14].

Craig and Raibert were the researchers who first proposed combining position and force information into one control scheme for moving the end effector in nondeterministic environments [4]. They called this scheme hybrid force/position control, currently referred to as hybrid control.

Later, the modification of this type of control scheme from a Cartesian formulation to a joint space formulation was done by Zhang and Paul using the same method for separating the position and force constraints in the Cartesian frame of interest [23]. In both cases, one beneficial factor of hybrid control is that the position and force information are analyzed separately to take advantage of well-known control techniques for each, and are combined only at the final stage when both have been converted to joint torques.

Afterwards, An and Hollerbach [1] proved that some accepted force control methods, including hybrid control, are unstable. Zhang found out that the hybrid control scheme may become unstable in certain manipulator configurations [22].

Whether we consider the force as disturbance or as desired force in the desired position, we need to use instruments for force measurement. One of the simple and most common methods for measuring force in robot arm is employing force sensor. Many researchers have used force sensors and position sensors to control the force and position of robots in different applications [2, 3, 8, 9, 11, 19, 20, 16, 18, 21]. Whitcomb et al. in 1997 has employed force sensor for controlling force in the desired position [21].

Practical applications for force sensor have not been common because of its difficulties such as high costs. For example, when the robot manipulator is under influence of environmental effects such as high temperature, large noise, etc, the force sensor cannot be mounted on it [10]. Furthermore, for those applications that force sensor can be simply employed, the sensor installation make the robot construction complicated [13]. Taking these problems into consideration, we should look for an appropriate method for replacing force sensor.

Whitcomb et al., five years after their previous research [21], introduced a new method to estimate force without any force sensor in 2003 [14]. Their method could be just employed for environments that can be modeled as stiffness (i.e. merely linear spring).

Danesh et al. in 2005 and 2006 introduced two approaches for estimating external force disturbances and canceling their effects [5, 6, 7]. In spite of many advantages of their approach one of its limitation is that the external force is required to be constant to guarantee the whole system stability.

In this paper, we keep all advantages of Danesh et al. approaches [5, 6, 7], and we can consider variable external force. It is worth to mention that in [5, 6, 7], the main problem is trajectory tracking and force is considered as an external disturbance.

However, in the proposed approach, the main problem is force control to achieve a desired force on a desired trajectory.

In [15], an algorithm is presented called force set point regulator (SPR). In [14] two hybrid force/position controllers are introduced named force trajectory tracking controller (TTC) and adaptive force tracking controller (TTCA), respectively.

In addition, using universal approximator features of fuzzy systems, the environment is modeled as a combination of (linear/nonlinear) springs, and (linear/nonlinear) dampers. Thus, friction parameters and also parameters of unknown environments can be estimated based on linguistic variable and fuzzy rules. Hence, the environment model is considered more general than that of [14]. Since the proposed approach is adaptive, the closed loop control system adapts itself with the environment parameter variation.

Organization of the paper follows. The proposed scheme to the fuzzy adaptive algorithm and its stability analysis, based on force estimation, are presented in section 2. To verify the performance of the proposed algorithm, simulation and comparative results of this approach are presented in section 3. The paper concludes in section 4.

2. **Adaptive Fuzzy Force Trajectory Tracking Controller (TTCAF) Design**

Consider dynamic equation of an n-link rigid manipulator with the force exerted by its end effector on environment and its reaction force, then one can write dynamic motion equation of the robot as

$$M(q)\ddot{q} + h(q,\dot{q}) = \tau + J^T(q)F_{ext} \tag{1}$$

where $q \in R^n$ is the vector of joint variables, $M(q)$ is the inertia matrix, $h(q,\dot{q})$ is the vector that includes Coriolis/centripetal and gravity torques, τ is the joint torque vector, and $J(q)$ is the Jacobian matrix.

Consider f_d as the desired and $\hat{f}$ as the estimated force vector in end-effector and define the force error vector as $\Delta f(t) = f_d(t) - \hat{f}(t)$. Also, define the force estimation error vector as $\tilde{f} = F_{ext} - \hat{f}$. In addition, let $q_d(t)$ as a given twice-differentiable desired trajectory in the joint space, and $e(t) = q_d(t) - q(t)$ defines the trajectory tracking error vector. Also, we assume that the motion equations of robot are given.

For obtaining control laws, stabilize the system with appropriate performance, at first the lemma 2.1 is reviewed, and then the stability of the closed loop system is guaranteed through theorem 2.2.

Lemma 2.1. *Suppose* $x = \left[y^T, r^T\right]^T$, $V_1(y)$ *is a positive definite function,* $\varphi_1 I \leq M(x,t) \leq \varphi_2 I$, *where* φ_1 *and* φ_2 *are positive scalars,* I *is the identity matrix, and* $V(x,y) = V_1(y) + \frac{1}{2}r^T M(x,y)r$

a) V *is positive definite and decrescent.*

b) If $V_1(y) = y^T By > 0$, *then* V *is radially unbounded.*

Proof. The reader is referred to [5, 6, 7] for the detailed proof. □

In this section, we present an adaptive fuzzy algorithm for estimation of the exerted force on the environment to overcome the problems of using force sensor in robot manipulators. The rule base of fuzzy system is a collection of fuzzy IF-THEN rules with n inputs and one output, whose Lth rules is in the following form:

$$R^{(L)} : IF\ x_1\ is\ {F_1}^L\ and \ldots and\ x_n\ is\ {F_n}^L\ THEN\ y\ is\ G^L \tag{2}$$

where F_i^L and G^L are fuzzy sets in $U \subset \Re$ and $V \subset \Re$, respectively, L=1,. . . ,N. $x = (x_1, ...x_n)^T \in U_1 \times ...U_n$ and $y \in V$ are linguistic variables. Gaussian membership function is used in this fuzzy logic system as

$$\mu_{{F_i}^L}(x_i) = \exp(-(\frac{x_i - x_i^L}{\sigma_i^L})^2) \tag{3}$$

where x_i^L and σ_i^L are respectively the center and the width of the fuzzy set associated with the Lth rule antecedent.

This system utilizes singleton fuzzifier and centre average defuzzifier product-inference rule as

$$F_{ext}^k(x) = \frac{\sum_{L=1}^{N_k} y_L^k(\Pi_{i=1}^n \mu_{F_i^L}^k(x_i))}{\sum_{L=1}^{N_k}(\Pi_{i=1}^n \mu_{F_i^L}^k(x_i))} \tag{4}$$

where $F_{ext}^k(x)$ is the output of the fuzzy system for the kth component of the generalized external force vector and N_k is the number of fuzzy IF-THEN rules in the form of (2) in the fuzzy rule base, n is the number of inputs (in this case two inputs, environment displacement and its derivative), y_L^k is the point at which output membership function achieves its maximum value (center of fuzzy set associated with each rule consequent).

Define $\zeta^k(x) = [\zeta_1^k, ..., \zeta_{N_k}^k]^T$ as the vector of fundamental fuzzy functions. It just depends on the antecedents of the fuzzy rules, where

$$\zeta_L^k(x) = \frac{\Pi_{i=1}^n \mu_{F_i^L}^k(x_i)}{\sum_{L=1}^{N_k}(\Pi_{i=1}^n \mu_{F_i^L}^k(x_i))}$$

also, define $\varphi^k = [y_1^k, ...y_{N_k}^k]^T$ as the fuzzy parameters vector and just depends on the consequent of the fuzzy rules. Hence, $F_{ext}^k(x) = (\zeta^k)^T \varphi^k$. If we define the matrix $\zeta(x) = \begin{bmatrix} \zeta^1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \zeta^m \end{bmatrix}$ and the vector $\varphi = [(\varphi^1)^T, ...(\varphi^m)^T]^T$ where m is the generalized force vector length, then we have

$$F_{ext} = \zeta^T(x)\varphi^* - w \tag{5}$$

where φ^* is the optimum parameters vector and w is the estimation error vector. Note that remembering the well-known universal approximation property (theorem) of fuzzy systems, the $\zeta^T(x)\varphi^*$ represents the optimum fuzzy approximation of F_{ext} using the fuzzy system with minimum error w.

Also, assume that $\hat{f}(t)$ and $\hat{\varphi}$ are respectively the estimations of F_{ext} and φ, consequently

$$\hat{f} = \zeta^T(x)\hat{\varphi} \tag{6}$$

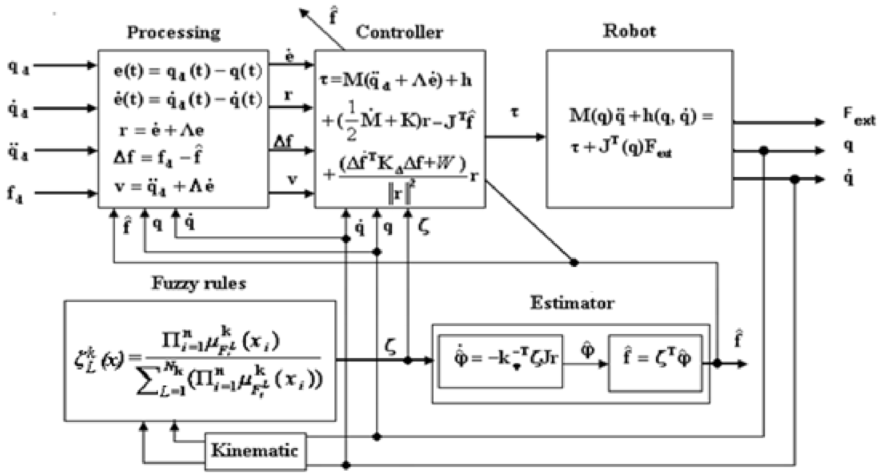


FIGURE 1. Block Diagram of Robot Adaptive Fuzzy Control System With Force Estimator (TTCAF)

Define $\tilde{\varphi} = \varphi^* - \hat{\varphi}$ as parameter estimation error. In order to design and guarantee the stability of the control system, theorem 2.2 is presented and proved.

Theorem 2.2. *Consider the robot control system of Figure 1 with the dynamic equation (1), the update law $\dot{\hat{\varphi}} = K_{\varphi}^{-T} \zeta J r$ and the control law*

$$\tau = \begin{cases} M(\ddot{q}_d + \Lambda\dot{e}) + h + (\frac{1}{2}\dot{M} + K)r - J^T\zeta^T\hat{\varphi} + \frac{(\Delta\dot{f}^T K_{\Delta}\Delta f + W)}{\|r\|^2} r & for\ \|r\| \neq 0 \\ 0 & for\ \|r\| = 0 \end{cases}$$

where Λ, K, K_{φ} and K_{Δ} are constant positive definite matrices and $r = \dot{e} + \Lambda e$, $\Lambda^T K = K^T \Lambda$ and $\left|r^T J^T w\right| \leq W$, where W is a known positive scalar. Then, the closed loop system is uniformly stable, the estimation error is bounded and the tracking error and its derivative go asymptotically to zero.

Proof. Substituting the control law into (1) and simplifying the result yields

$$M\dot{r} + (\frac{1}{2}\dot{M} + K)r + J^T\zeta^T\tilde{\varphi} + \frac{(\Delta\dot{f}^T K_{\Delta}\Delta f + W)}{\|r\|^2} r + J^T w = 0 \tag{7}$$

Thus regarded to invertibility of M, one can write

$$\dot{r} = -M^{-1}(\frac{1}{2}\dot{M} + K)r - M^{-1}J^T\zeta^T\tilde{\varphi} - M^{-1}\frac{(\Delta\dot{f}^T K_{\Delta}\Delta f + W)}{\|r\|^2} r - M^{-1}J^T w \tag{8}$$

On the other hand, time derivative of Δf is

$$\Delta\dot{f} = \dot{f}_d - \dot{\hat{f}} \tag{9}$$

replacing (6) in (9) and substituting the control law, we have

$$\Delta\dot{f} = \dot{f}_d - \dot{\zeta}^T\hat{\varphi} + \zeta^T K_{\varphi}^{-T}\zeta J r \tag{10}$$

Considering the update law, (8), (10) state equations of the closed loop system can be presented as

$$\begin{aligned} &\dot{e} = -\Lambda e + r \\ &\dot{r} = -M^{-1}(\tfrac{1}{2}\dot{M} + K - \tfrac{(\Delta\dot{f}^T K_\Delta \Delta f + W)}{\|r\|^2} I)r - M^{-1}J^T\zeta^T\tilde{\varphi} - M^{-1}J^T w \\ &\dot{\tilde{\varphi}} = K_{\varphi}^{-T}\zeta J r \\ &\Delta\dot{f} = \dot{f}_d - \dot{\zeta}^T\hat{\varphi} + \zeta^T K_{\varphi}^{-T}\zeta J r \end{aligned} \tag{11}$$

Now we can choose a candidate Lyapunov function in terms of variables of the whole system $x = \left[e^T, r^T, \tilde{\varphi}^T, \Delta f^T\right]^T$ as

$$V(x,t) = e^T\Lambda^T K e + \frac{1}{2}(\dot{e} + \Lambda e)^T M(\dot{e} + \Lambda e) + \frac{1}{2}\tilde{\varphi}^T K_{\varphi}\tilde{\varphi} + \frac{1}{2}\Delta f^T K_\Delta \Delta f \tag{12}$$

If we rewrite V in terms of e, r, $\tilde{\varphi}$ and Δf, then

$$V = e^T\Lambda^T K e + \frac{1}{2}r^T M r + \frac{1}{2}\tilde{\varphi}^T K_{\varphi}\tilde{\varphi} + \frac{1}{2}\Delta f^T K_\Delta \Delta f \tag{13}$$

This equation can be represented by

$$V = y^T B y + \frac{1}{2}r^T M r, \tag{14}$$

where $y = \left[e^T, \tilde{\varphi}^T, \Delta f^T\right]^T$ and $B = \begin{bmatrix} \Lambda^T K & 0 & 0 \\ 0 & \frac{1}{2}K_{\varphi} & 0 \\ 0 & 0 & \frac{1}{2}K_\Delta \end{bmatrix}$. Based on Lemma 2.1, matrix B is positive definite then V is radially unbounded. Also time derivative of (13) is

$$\dot{V} = 2e^T\Lambda^T K\dot{e} + r^T M\dot{r} + \frac{1}{2}r^T\dot{M}r + \dot{\tilde{\varphi}}^T K_{\varphi}\tilde{\varphi} + \Delta\dot{f}^T K_\Delta \Delta f \tag{15}$$

Substituting $\ddot{e}$ by $\ddot{q}_d - \ddot{q}$ and replacing $M\ddot{q}$ from (1), we have

$$\dot{V} = 2e^T\Lambda^T K\dot{e} + r^T(M\ddot{q}_d + h - \tau - J^T F_{ext} + M\Lambda\dot{e} + \frac{1}{2}\dot{M}r) + \dot{\tilde{\varphi}}^T K_{\varphi}\tilde{\varphi} + \Delta\dot{f}^T K_\Delta \Delta f \tag{16}$$

Now, substituting $F_{ext}(5)$ and the control law

$$\tau = M(\ddot{q}_d + \Lambda\dot{e}) + h + (\frac{1}{2}\dot{M} + K)r - J^T\zeta^T\hat{\varphi} + \frac{(\Delta\dot{f}^T K_\Delta \Delta f + W)}{\|r\|^2}r \tag{17}$$

into (16) and doing some mathematical manipulations, we get

$$\dot{V} = 2e^T\Lambda^T K\dot{e} - r^T K r + \dot{\tilde{\varphi}}^T K_{\varphi}\tilde{\varphi} - r^T J^T\zeta^T\tilde{\varphi} + (r^T J^T w - W) \tag{18}$$

Considering the assumption

$$\left|r^T J^T w\right| \le W \tag{19}$$

and the update law

$$\dot{\tilde{\varphi}} = K_{\varphi}^{-T}\zeta J r \tag{20}$$

and doing some mathematical manipulations we have

$$\dot{V} \le -e^T\Lambda^T K\Lambda\, e - \dot{e}^T K\dot{e} \tag{21}$$

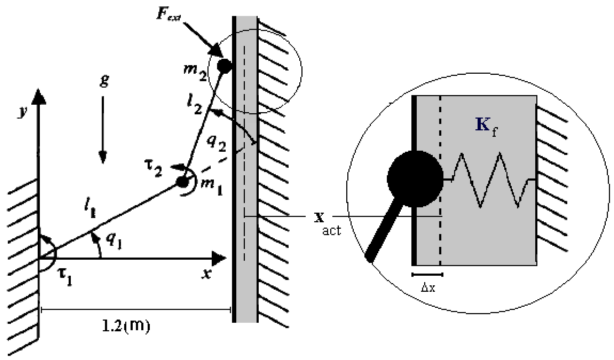


FIGURE 2. 2-DOF Manipulator and Environment

Since Λ, K are constant positive definite matrices we have $\dot{V} \leq 0$, $\forall x \in R^P$, $\forall t \geq 0$. $V > 0$ is decrescent, continuous time and radially unbounded in terms of the state vector $x = \left[e^T, r^T, \tilde{\varphi}^T, \Delta f^T\right]^T$.

Thus, based on the Lyapunov direct method for non-autonomous system [17], the system with the state equation (11) is uniformly stable. As a result, $\tilde{\varphi}$ and Δf are bounded. Furthermore, since $V(x,t)$ is lower bounded and $\dot{V}(x,t)$ is negative semi-definite and uniformly continuous in time, by using lemma 4.3 of [17] $\lim_{t\to\infty} \dot{V}(x,t) = 0$, therefore $\lim_{t\to\infty} e = 0$ and $\lim_{t\to\infty} \dot{e} = 0$. □

Remark 2.3. Due to the fact that when r is very small the torque is large in the last term of the control law and also considering the limitation of torque in physical actuator we limit the last term of the control law in our simulations.

3. **Simulation and Comparative Results**

In this section, control scheme (TTCAF) which is presented in section 2 is simulated on a two DOF planar type robot manipulator depicted in Figure 2 to show the efficiency of this scheme.

Gray color part in Figure 2 shows the environment displacement. It is worth to mention that environment displacement depends on the desired force and environment specification of each point. Also, this displacement is usually very small and is illustrated in Figure 2 very larger than its real value. We compare the simulation results of the proposed approaches with that of three mentioned controllers.

$$h(q,\dot{q}) = \begin{bmatrix} -m_2 l_1 l_2 (2\dot{q}_1\dot{q}_2 + \dot{q}_2^2)\cos q_2 \\ m_2 l_1 l_2 \dot{q}_1^2 \sin q_2 \end{bmatrix} + \begin{bmatrix} (m_1+m_2) g l_1 \cos q_1 + m_2 g l_2 \cos(q_1+q_2) \\ m_2 g l_2 \cos(q_1+q_2) \end{bmatrix}$$

$$J(q) = \begin{bmatrix} -l_1 \sin q_1 - l_2 \sin(q_1+q_2) & -l_2\sin(q_1+q_2) \\ l_1\cos q_1 + l_2\cos(q_1+q_2) & l_2\cos(q_1+q_2) \end{bmatrix}$$

where m_i, l_i and q_i are the mass of ith link, the length of ith link and the angle of ith joint, respectively.

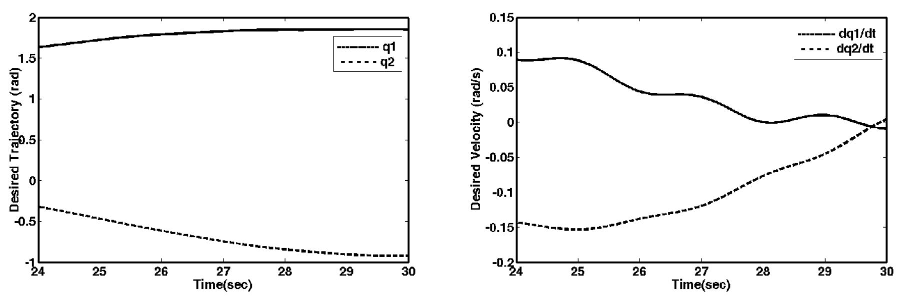
To compare the results with the previous works, the environment is the same as [14], i.e., thin spring steel beam rigidly fixed at one end with the other end free. For small displacements of the free end, this beam approximates an environment with linear compliance.

As depicted in Figure 2 this surface is located in 1.2 meter far from the robot base and modeled by linear spring with constant $K_f = 86.9(N/m)$ therefore in this case the external force is equal to $K_f \Delta x$. The desired trajectory is set to be $x_d(t) = [1.2, (0.5\cos(\pi/10)t + 0.5)]^T(\mathrm{m})$. It is obvious that the actual trajectory must be $x_{act}(t) = [1.2 + \Delta x, (0.5\cos(\pi/10)t + 0.5)]^T$ to obtain proper results. The initial conditions of robot are assumed to be $x(0) = [1.2,\ 1]^T\ (m)$ and $\dot{x}\ (0) = [0, 0]^T(m/s)$.

The numerical values of the robot parameters are:
$l_1 = l_2 = 1\,(m)$,$m_1 = m_2 = 1(Kg)$ and $g = 9.8(m/s^2)$. Let the parameters of control system as $K = diag\,(100\,,80)$, $K_\Delta = \Lambda = I_2$ and $K_\varphi = 0.001I_{25}$ where I_N is the $N \times N$ identity matrix.

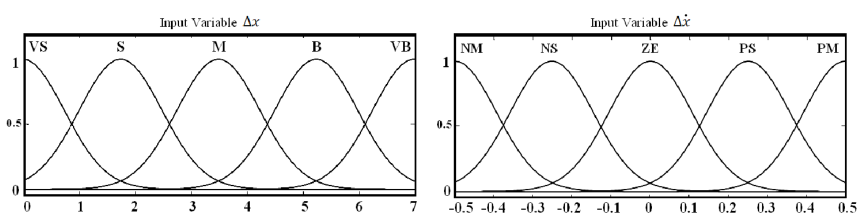
The desired forced in these simulations is $f_d = [0.3 + 0.2\sin\pi t, 0]^T$ and the initial value of $\hat{f}$ is $\hat{f}(0) = [0, 0]^T$. Figure 3 presents the desired trajectories and the desired velocities in the joint space that obtained through inverse kinematics.

The fuzzy estimator in TTCAF has Gaussian memberships function for each input that characterize the fuzzy sets in the form of (4) as shown in Figure 4.



(A) Desired Trajectory (B) Desired Velocity

FIGURE 3. Desired Trajectory and Velocity in Joint Space when the Robot Moves along Y-axis



(A) Position (B) Velocity

FIGURE 4. Membership Functions in the Adaptive Fuzzy Estimator

$\Delta\dot{x}/\Delta x$	VS	S	M	L	VL
NM	VS	VS	S	S	M
NS	VS	S	S	M	M
ZE	S	S	M	M	L
PS	S	M	M	L	L
PM	M	M	L	L	VL

Table 1. Rule Base of Fuzzy Estimator

There are five fuzzy sets for Δx named, VS (Very Small), S (Small), M (Medium), L (Large), and VL (Very Large) and five fuzzy sets for $\Delta\dot{x}$, named, NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), and PM (Positive Medium). As it is shown in Figure 4 Δx is always positive but $\Delta\dot{x}$ may be positive or negative in general. The 25 fuzzy inference rules derived by the expert are shown in Table 1. For example one of the laws states that if the position is very large and the velocity is negative and small, then the external force is medium. They are based on the combination of the five fuzzy membership functions of Δx and the five fuzzy membership functions of $\Delta\dot{x}$. It is obvious that in this simple linear environment $\Delta\dot{x}$ doesn't influence the external force and fuzzy rules decrease to only 5 rules presented in third row of Table.1

Some simulations are done in order to show the necessity of using the force signal in the control law. Figure 5 shows the results of the case that the control system of the robot does not include force sensor or estimator. As observed, the robot cannot track the desired trajectory appropriately also velocity errors and torque have undesirable high frequency fluctuations.

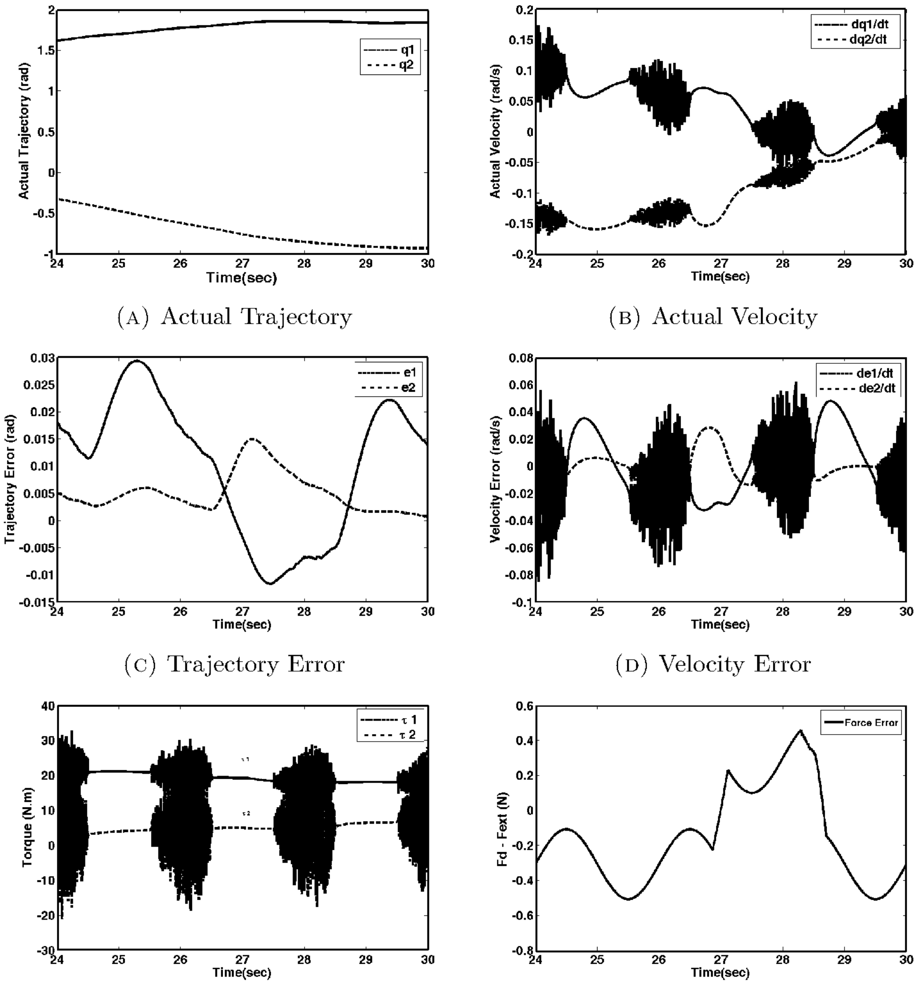
Now if a force sensor is mounted on the end-effector, the force signal is measured and can be applied to the control law i.e. $\hat{f} = F_{ext}$ and the force estimation error $\tilde{f} = 0$.

The results of this case are depicted in Figure 6. The tracking error tends to zero and the velocity and torque responses are excellent. Therefore, force measurement is critical and essential for proper trajectory tracking performance.

Also, as observed the external force converges to the desired force satisfactorily. Note that the trajectory, velocity and force errors in Figure 6 are very small and in the range of less than 10^{-4}.

However, as mentioned in the introduction, there are some situations that mounting force sensor on robot faces difficulty. Hence, it is required to supply force value by estimating force for these situations. For the sensorless control system proposed in section 2 (TTCAF); the trajectory and velocity errors decrease as illustrated in Figure 7.

Also, external force converges to the desired force because the adaptive fuzzy estimator can satisfactory estimate the desired force as depicted in Figure 8.



(A) Actual Trajectory (B) Actual Velocity

(C) Trajectory Error (D) Velocity Error

(E) Torque (F) Force Error

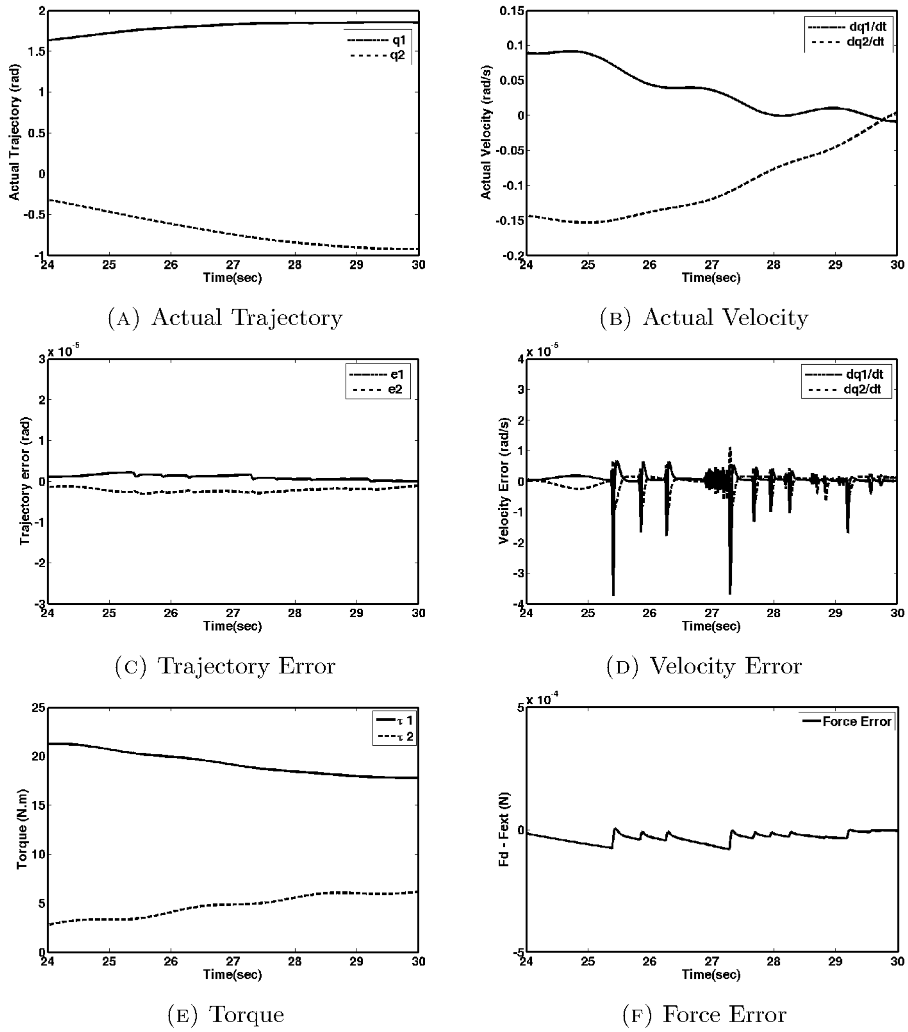
Figure 5. Without Force Sensor, (A) q, (B)$\dot{q}$, (C) e, (D)$\dot{e}$, (E)τ, (F)$f_d - F_{ext}$

To evaluate the force tracking performance of the sensorless controllers (SPR, TTC, TTCA, and TTCAF) the force trajectory is considered as $f_d = 0.3{+}0.2\sin 2\pi t$ (N).

According to Figure 8, the force tracking errors for this reference trajectory are $\pm$10% for the SPR controller, $\pm$2.5% for the TTC controller, about $\pm$2% for the TTCA and less than $\pm$1.5% for the TTCAF controller.

Figure 8 shows the reference and actual force trajectories of each control system as well as its force tracking errors in following a reference trajectory of 0.5 Hz.

At last, to show the results in the whole time interval of the simulations, the trajectory, velocity and force errors of the TTCAF controller are depicted in the



(A) Actual Trajectory (B) Actual Velocity

(C) Trajectory Error (D) Velocity Error

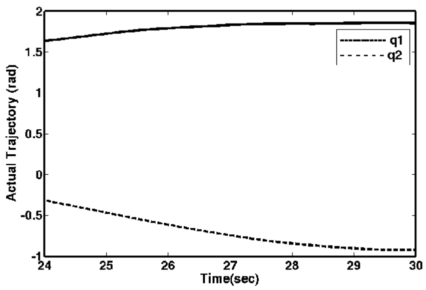
(E) Torque (F) Force Error

FIGURE 6. With Force Sensor, (A) q, (B)$\dot{q}$, (C) e, (D)$\dot{e}$, (E)τ, (F)$f_d - F_{ext}$

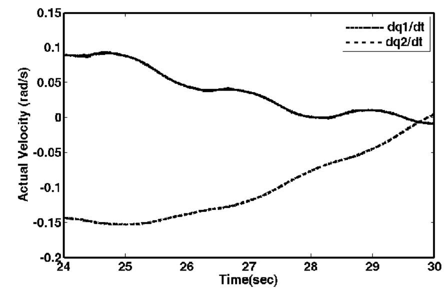
Figure 9. On the whole, the results of this section illustrate that the proposed adaptive fuzzy scheme works satisfactorily and effectively. Thus, the presented estimator can be properly replaced for force sensor in a robot manipulator.

4. Conclusions

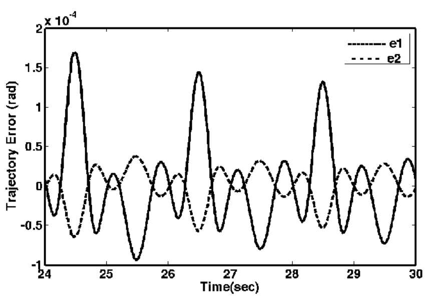
In this paper, one scheme has been introduced for force/position control. As shown this scheme is stable and there is no need to assume that joint trajectory, velocity and acceleration are bounded; the knowledge of force direction is not necessary; measurement or computation of the joint accelerator and considering the inertia matrix as a constant diagonal matrix are not required; the convergence of tracking error is independent of initial configuration; the scheme is not developed for special type of rigid manipulators and as seen in the simulations of the paper the controller gain is not too large. This scheme is suitable for some situations that have difficulty in mounting force sensor or require the elimination of expensive force sensor; this scheme uses an adaptive fuzzy force estimator. Stability and boundedness of estimation error and convergence of tracking error were proved through one theorem for this scheme. A number of simulations were presented for desired



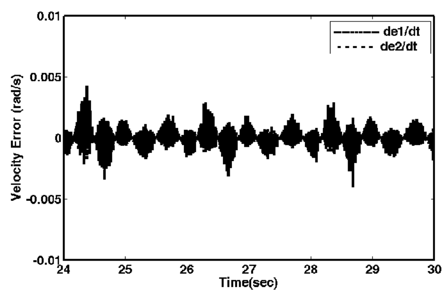
(A) Actual Trajectory



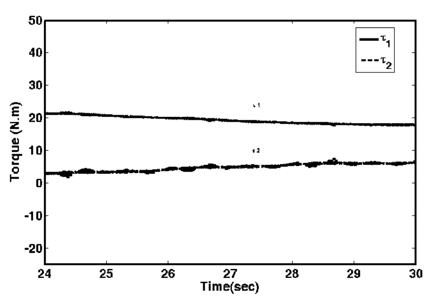
(B) Actual Velocity



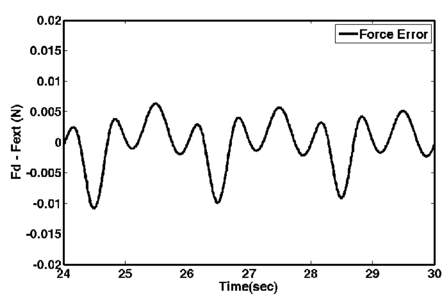
(C) Trajectory Error



(D) Velocity Error

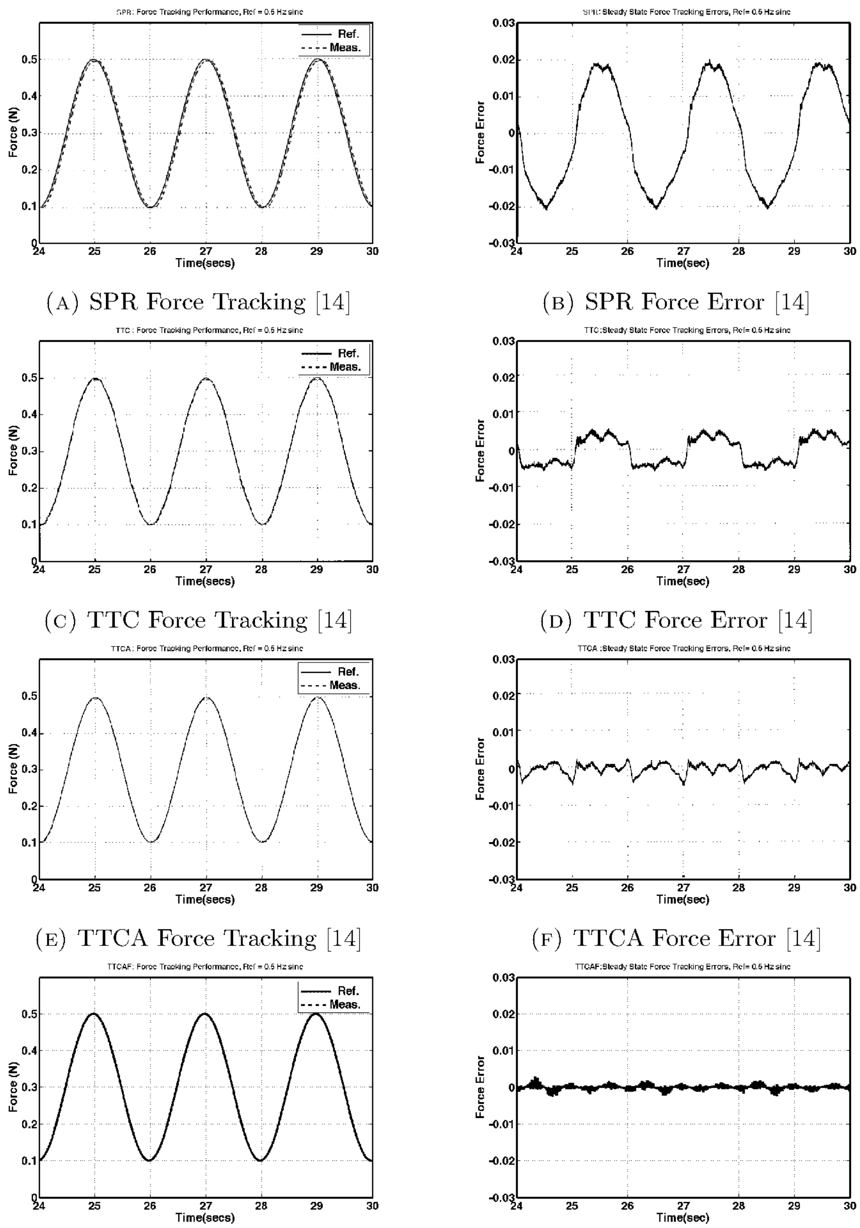


(E) Torque



(F) Force Error

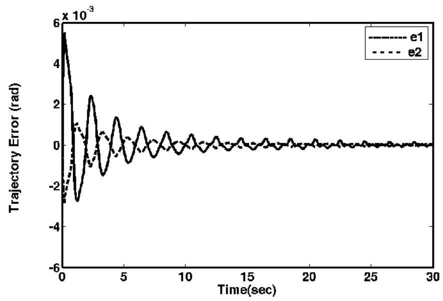
FIGURE 7. With Force Estimator, (A) q, (B)$\dot{q}$, (C) e, (D)$\dot{e}$, (E)τ, (F)$f_d - F_{ext}$



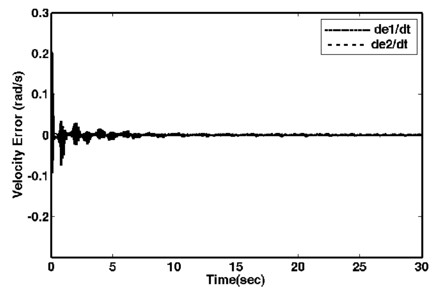
(A) SPR Force Tracking [14]
(B) SPR Force Error [14]
(C) TTC Force Tracking [14]
(D) TTC Force Error [14]
(E) TTCA Force Tracking [14]
(F) TTCA Force Error [14]
(G) TTCAF Force Tracking
(H) TTCAF Force Error

Figure 8. Force Tracking Performances of Different Controllers

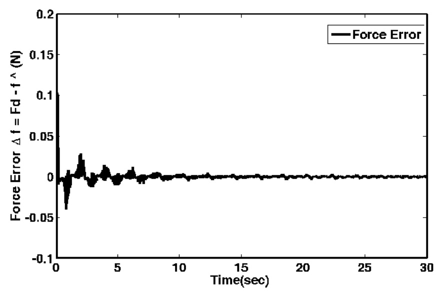
external force on a desired trajectory. The results exhibited excellent force/position tracking and satisfactory estimation performance of the proposed control system.



(A) Trajectory Error



(B) Velocity Error



(C) Force Error

Figure 9. Errors in the Whole Time Interval in TTCAF

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