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Position/Force Control for Robot Manipulators Without Force and Velocity Measurements

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Abstract

The paper proposes a new adaptive control method to control the position and force of the robot manipulators without velocity and force measurements. This method is performed by a combination of a position and force adaptive control algorithm with a force/velocity observer. With GPI technique (Generalized Proportional Integral), the force/velocity observer is designed to give estimates of force and velocity to feedback to the controller. The control algorithm is based on Slotine-Li's adaptive position control law and is added a component that controls the interaction force between the end-effector of robot manipulators with the environment. In addition, a parameter updating law is designed to adapt to the change in dynamic parameters when the robot manipulators work under environmental constraints. Simulations are made on the Matlab Simulink software to demonstrate the results of the algorithm.

Keywords: Force control, GPI technique, force control without force sensor, hybrid force/position control, adaptive control

1. Introduction[1]

In the applications of robot manipulators that interact with the environment such as assembly, milling, pulling and handling requirements, the end-effector position and force must be controlled. Most control approaches are impedance [1, 2] and hybrid position/force control [3], which separated the control tasks into two subspaces. These approaches usually are assumed with an accurate dynamic model and the measurements of force, velocity, and position [4, 5]. There are disadvantages in using sensors, e.g., the effects of noise, overall weight, and costs. An open-loop force controller which does not require any velocity/force measurements is proposed in [6]. In [7], a control scheme used a linear observer to replace the velocity sensors with an open-loop force control. A Generalized Proportional Integral Observer was introduced in [8]. A force/velocity observer is also designed to control force/position using a simple PID law with the certainties of dynamic model and payload parameters [9]. On the other hand, adaptive control is a strategy for solving problems about disturbances and unknown parameters during working of robot manipulators. Several studies have been proposed [10-12] consequently to estimate the external force using adaptive approaches. A combination of an extended Kalman filter for states estimation and an adaptive law to estimate the force for the controller of manipulator [13]. An adaptive scheme is proposed for robot manipulator that perform an interaction task with rigid surface [14]. In this work, both the robot and constraint surface parameters are uncertain. In [15], a research was devoted to sensorless adaptive force/position control of robot manipulators using a position-based adaptive force estimator (AFE) and a force-based an adaptive environment compliance estimator. In this method, the unknown parameters of the robot can be estimated along with the force control. This work did not require force sensors, and it was assumed that had unknown environment stiffness and parametric uncertainties. An application of GPI observer has also been used to design a force controller with unknown perturbations and a certain number of its time derivatives in an arbitrarily close manner [16].

In this paper, an adaptive position/force control law is developed from Slotine'algorithm to adapt to the change of dynamic parameters of robot manipulators during working. In addition, a force/velocity observer is also designed by GPI technique to estimate the feedback signals of force and velocity. The organization of the paper is as follows: Section 2, describes the basic analysis of constrained movement in contact with the environment. Section 3 is devoted to design force/velocity observer and to develop control algorithm. The simulation results are presented in

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section 4. The concluding remarks are finally given in section 5

2. Analysis of constrained movement in contact with environment

Consider a n-degree of freedom robot manipulator in constrained movement with environment [16]

$$H(q)\ddot{q}+C(q,\dot{q})\dot{q}+D\dot{q}+g(q)=\tau+J_{\varphi}^{T}(q)\lambda \quad (1)$$

where $q\in\mathbb{R}^{n}$ is the vector of generalized coordinates, $\dot{q}\in\mathbb{R}^{n}$ and $\ddot{q}\in\mathbb{R}^{n}$ are velocity and acceleration vectors, $H(q)\in\mathbb{R}^{n\times n}$ is the inertia matrix, (is the symmetric positive definite matrix) $C(q,\dot{q})\in\mathbb{R}^{n}$ is vector of the Coriolis and centrifugal torque, $g(q)\in\mathbb{R}^{n}$ is the vector of gravitational torques, $D\in\mathbb{R}^{n\times n}$ is the diagonal semidefinite positive matrix of viscous friction coefficients, $\tau\in\mathbb{R}^{n}$ is the vector of input torques acting at the joints, $\lambda\in\mathbb{R}^{n}$ is the Lagrange multipliers vector (physically represents the force exerted by manipulator on the environment at the contact point), and $J_{\varphi}(q)=\nabla\varphi(q)\in\mathbb{R}^{m\times n}$ it denotes the gradient of the holonomic constraint.

When the robot manipulator is in contact with the environment, constrained equation is composed as.

$$\varphi(q)=0 \quad (2)$$

Take the derivative of equation (2), yields

$$\dot{\varphi}(q)=J_{\varphi}(q)\dot{q}=0 \quad (3)$$

where

$$J_{\varphi}(q)=\frac{\partial\varphi}{\partial q} \quad (4)$$

In case that robot contact with the constraint in joint space, orthogonal decomposition of space is composed. If matrices $P(q)$ and $Q(q)$ are projectors.

With the above analysis, the velocity vector $\dot{q}$ can be written by

$$\dot{q}=Q(q)\dot{q}+P(q)\dot{q} \quad (5)$$

where, $Q(q)=I_{n\times n}-P(q)$, with $P(q)=J_{\varphi}^{\dagger}J_{\varphi}$ and $J_{\varphi}^{\dagger}=J_{\varphi}^{T}(J_{\varphi}J_{\varphi}^{T})^{-1}\in\mathbb{R}^{n\times m}$ is pseudoinverse matrix and $Q(q)\in\mathbb{R}^{n\times n}$ with $rank(Q)=n-m$. In here, $Q(q)$ can be regarded as a projection matrix. This matrix projects vectors in joint space onto the plane that tangent to the surface $\varphi(q)=0$ at point of q

Because of $P(q)$ and $Q(q)$ are orthogonal matrices so $Q(q)P(q)=O$, $Q(q)J_{\varphi}^{T}=O$ and $J_{\varphi}Q(q)=O$

Eq. (3) presents $P(q)\dot{q}=0$, substituting into (5), can be rewritten by

$$\dot{q}=Q(q)\dot{q}+P(q)\dot{q}=Q(q)\dot{q} \quad (6)$$

3. Adaptive force/position controller with velocity/force observer

In this section, there are two proposed contents ei., velocity/force observer is designed by GPI technique and the adaptive force/position controller uses observer that be designed. Considering dynamic equation is given (1) with variables are joints angle. They are written in state space form by defining

$$x=\begin{bmatrix}x_1\\x_2\end{bmatrix}=\begin{bmatrix}q\\\dot{q}\end{bmatrix} \quad (7)$$

So that Eq. (1) can be written as

$$\dot{x}_1=x_2 \quad (8)$$

$$\begin{aligned}\dot{x}_2&=H^{-1}(x_1)\left[\tau-C(x_1,x_2)x_2-Dx_2-g(x_1)\right]\\&+H^{-1}(x_1)J_{\varphi}^{T}(x_1)\lambda\end{aligned} \quad (9)$$

To simplify the notations and use to design force/velocity observer, we assign the values as following

$$z_1\triangleq H^{-1}(x_1)J_{\varphi}^{T}(x_1)\lambda \quad (10)$$

$$N(x_1,x_2)\triangleq C(x_1,x_2)x_2+Dx_2+g(x_1) \quad (11)$$

Substituting (10) and (11) into (9) one get

$$\dot{x}_2=H^{-1}(x_1)\left[\tau-N(x_1,x_2)\right]+z_1 \quad (12)$$

The purpose of this approach is to design an observer to estimate in a way an approximate force λ that is the interaction between the end-effector of the robot manipulator with the environment. However, this force can be proposed as an internal representation for the z_1. On the other hand, z_1 and λ are considered unknown terms and estimated by GPI technique [17] with assumptions are given as.

Assumption 1:

Derivatives at least k of $r^{(k)}(t)$ and components of $z_1(t)$ are absolutely uniformly bounded with every bounded trajectory $q(t)$ [8].

Assumption 2:

$z_1(t)$ can be rewritten as sum of an element of $k-1$-degree family of polynomials and a residual term

$$z_1(t)=\sum_{i=0}^{k-1} a_i t^i + r(t) \tag{13}$$

where a_i is a n-vector of constant coefficients and vector $z_1(t)$ is written in state space ei.,

$$\begin{aligned}\dot{z}_1 &= z_2\\ \dot{z}_2 &= z_3\\ &\vdots\\ \dot{z}_{k-1} &= z_k\\ \dot{z}_k &= r^{(k)}(t)\end{aligned} \tag{14}$$

GPI observer is proposed as

$$\dot{\hat{x}}_1 = \hat{x}_2 + \lambda_{k+1}\tilde{x}_1 \tag{15}$$

$$\dot{\hat{x}}_2 = H^{-1}(q)\left[\tau - N(x_1,\hat{x}_2)\right] + \hat{z}_1 + \lambda_k \tilde{x}_1 \tag{16}$$

$$\begin{aligned}\dot{\hat{z}}_1 &= \hat{z}_2 + \lambda_{k-1}\tilde{x}_1\\ \dot{\hat{z}}_2 &= \hat{z}_3 + \lambda_{k-2}\tilde{x}_1\\ &\vdots\\ \dot{\hat{z}}_{k-1} &= \hat{z}_k + \lambda_1\tilde{x}_1\\ \dot{\hat{z}}_k &= \lambda_0\tilde{x}_1\end{aligned} \tag{17}$$

errors of above observer as

$$\tilde{x}_1 \triangleq x_1 - \hat{x}_1 \tag{18}$$

$$\tilde{x}_2 \triangleq x_2 - \hat{x}_2 \tag{19}$$

$$\tilde{z}_i \triangleq z_i - \hat{z}_i \tag{20}$$

With $i = 1,...,k$.

The $n\times n$ diagonal constant matrices $\lambda_0,\lambda_1,...,\lambda_{k+1}$ are chosen such that the roots of associated polynomial in the complex variable s

$$P(s) = s^{k+2}I + \lambda_{k+1}s^{k+1} + ... + \lambda_1 s + \lambda_0 \tag{21}$$

are located on the left half of the complex plane. With these choices, the observer drives estimation error asymptotically to an arbitrarily small neighborhood of origin.

$$(\tilde{x}_1,\tilde{x}_2,\tilde{z}_1,\tilde{z}_2,...,\tilde{z}_k) = (0,...,0) \tag{22}$$

From (10), force estimation is computed as

$$\hat{z}_1 \approx H^{-1}(x_1)J_\varphi^T(x_1)\hat{\lambda} \tag{23}$$

Substituting $J_\varphi = J_{\varphi x}J(q)$ into (23) one gets

$$\hat{z}_1 = H^{-1}(q)J^T(q)J_{\varphi x}^T\hat{\lambda} \tag{24}$$

$\hat{\lambda}$ can be computed as

$$\hat{\lambda} = \left(J_{\varphi x}^{\dagger}\right)^T J^{-T}(q)H(q)\hat{z}_1 \tag{25}$$

where, $J_{\varphi x}^{\dagger}$ is the same $J_\varphi^{\dagger}$

$$J_{\varphi x}^{\dagger} = J_{\varphi x}^T\left(J_{\varphi x}J_{\varphi x}^T\right)^{-1} \tag{26}$$

Now, an adaptive force/position control law is proposed by using the force/ velocity observer. In this case, the only position is measured by angle sensors. Because of robot's dynamic is the linear parameterization property, motion equations can be rewritten as

$$H(q)\ddot{q} + C(q,\dot{q})\dot{q} + D\dot{q} + g(q) = Y(q,\dot{q},\dot{q},\ddot{q})\mathbf{p} \tag{27}$$

Where $Y(q,\dot{q},\dot{q},\ddot{q})$ is regression matrix and $\mathbf{p} = [p_1, p_2,..., p_\ell]^T$ is parameter vector that depends on masses and inertial of links of the robot manipulator. Nominal reference of $\dot{q}$ is defined as

$$\dot{q}_r = Q(q)(\dot{q}_d - Le) + \eta J_\varphi^T \Delta F \tag{28}$$

Where L is a positive definite diagonal matrix, $\eta \ge 0$ is constant. In here, $\dot{q}_r$ is divided into two parts that are orthogonal to each other. The errors of position and force are computed by

$e = q - q_d$, $\dot{e} = \hat{x}_2 - \dot{q}_d$ and $\Delta F = \int_0^T \Delta\lambda(\tau)d\tau$

with $\Delta\lambda = \hat{\lambda} - \lambda_d$

Where $\hat{\lambda}$ and $\hat{x}_2$ are estimation values of force and velocity that are taken from the observer. The residual signal between corresponding of velocity $\dot{q}$ and nominal reference $\dot{q}_r$ is defined as

$$s = s_t + s_n = Q(\dot{e} + Le) - \eta J_\varphi^T \Delta F \tag{29}$$

where $s_t = Q(\dot{e} + Le)$ presents tangent direction with environment surface at the contact point and $s_n = -\eta J_\varphi^T \Delta F$ also presents normal direction.

To design this adaptive controller, $\dot{q}$ and $\ddot{q}$ are replaced by $\dot{q}_r$ and $\ddot{q}_r$, so (27) can be written by

$$H(q)\ddot{q}_r + C(q,\dot{q})\dot{q}_r + D\dot{q} + g(q) = Y(q,\dot{q},\dot{q}_r,\ddot{q}_r)\mathbf{p} \quad (30)$$

With the adaptive control law is proposed by E. Slotine and Weiping Li [18], a modified adaptive control law is proposed i.e.,

$$\tau = -K_d s + Y\left(q,\dot{\hat{q}},\dot{q}_r,\ddot{q}_r\right)\hat{\mathbf{p}} - J_\varphi^T\left(\lambda_d - \mu\Delta F\right) \quad (31)$$

Where $\mu \geq 0$ is constant and $\hat{\mathbf{p}}$ is an estimation at time t of unknown parameters $\mathbf{p}$. At any time, estimated value of $\hat{\mathbf{p}}$ will be updated with followed adaptive law

$$\dot{\hat{\mathbf{p}}} = -\Gamma^{-1}Y^T\left(q,\dot{\hat{q}},\dot{q}_r,\ddot{q}_r\right)s \quad (32)$$

where Γ is a positive definite diagonal matrix. In control law (31) and adaptive law (32), joints velocity $\dot{q}$ and contact force λ are estimated by observer. These signals are sequentially $\hat{x}_2 \equiv \dot{\hat{q}}$ and $\hat{\lambda}$.

Proof:

Substituting the control law (30) into (1) yields

$$Y(q,\dot{q},\dot{q},\ddot{q})\mathbf{p} - Y\left(q,\dot{\hat{q}},\dot{q}_r,\ddot{q}_r\right)\hat{\mathbf{p}} = J_\varphi^T\left(\xi\lambda + \mu\Delta F\right) - K_d s \quad (33)$$

Where $\xi\lambda = \lambda - \lambda_d$. From (22), we can conclude that estimation errors of force and velocity converge to zero so $\hat{\lambda} \to \lambda$ and $\dot{\hat{q}} \to \dot{q}$ when $t \to \infty$. Equation (33) can be written as

$$\begin{aligned} &\left\{Y(q,\dot{q},\dot{q},\ddot{q})\mathbf{p} - Y(q,\dot{q},\dot{q}_r,\ddot{q}_r)\mathbf{p}\right\} \\ &+\left\{Y(q,\dot{q},\dot{q}_r,\ddot{q}_r)\mathbf{p} - Y(q,\dot{q},\dot{q}_r,\ddot{q}_r)\hat{\mathbf{p}}\right\} \\ &= J_\varphi^T\left(\xi\lambda + \mu\Delta F\right) - K_d s \end{aligned} \quad (34)$$

where

$$\begin{aligned} s &= \dot{q} - \dot{q}_r \\ \dot{s} &= \ddot{q} - \ddot{q}_r \end{aligned} \quad (35)$$

Combination of (34) and (35) yields

$$Y(q,\dot{q},s,\dot{s})\mathbf{p} - Y(q,\dot{q},\dot{q}_r,\ddot{q})\Delta\mathbf{p} = J_\varphi^T\left(\xi\lambda + \mu\Delta F\right) - K_d s \quad (36)$$

Where $\Delta\mathbf{p} = \hat{\mathbf{p}} - \mathbf{p}$ and $Y(q,\dot{q},\dot{q},\ddot{q})\mathbf{p}$ can be written by different form as

$$\begin{aligned} &Y(q,\dot{q},\dot{q},\ddot{q})\mathbf{p} = H(q)\ddot{q} + g(q) \\ &+\left\{M_0 + \frac{1}{2}\dot{H}(q) + S(q,\dot{q}) + \zeta\left(\|J\dot{q}\|\right)J^T J\right\}\dot{q} \end{aligned} \quad (37)$$

and

$$\begin{aligned} &Y(q,\dot{q},\dot{q}_r,\ddot{q}_r)\mathbf{p} = H(q)\ddot{q}_r + g(q) \\ &+\left\{M_0 + \frac{1}{2}\dot{H}(q) + S(q,\dot{q}) + \zeta\left(\|J\dot{q}\|\right)J^T J\right\}\dot{q}_r \end{aligned} \quad (38)$$

Where M_0 presents damping factor of system and is a positive definite matrix, $\zeta\left(\|\dot{x}\|\right)$ is a positive function of $\|\dot{x}\|$ and $\zeta\left(\|\dot{x}\|\right)$ presents viscous friction of system. Where $\dot{x} = J(q)\dot{q}$, from (35), (37) and (38) yields

$$\begin{aligned} &Y(q,\dot{q},s,\dot{s})\mathbf{p} = H(q)\dot{s} \\ &+\left\{M_0 + \frac{1}{2}\dot{H}(q) + S(q,\dot{q}) + \zeta\left(\|J\dot{q}\|\right)J^T J\right\}s \end{aligned} \quad (39)$$

where $\hat{\mathbf{p}}$ is estimation parameters of unknown parameters $\mathbf{p}$, and $\hat{\mathbf{p}}$ can be updated by adaptive law of dynamic parameters as

$$\hat{\mathbf{p}}(t) = \hat{\mathbf{p}}(0) - \int_0^T \Gamma^{-1}Y^T\left(q,\dot{q},\dot{q}_r,\ddot{q}_r\right)s(\tau)d\tau \quad (40)$$

Derivation of (40) yields

$$\frac{d}{dt}\Delta\mathbf{p} = -\Gamma^{-1}Y^T\left(q,\dot{q},\dot{q}_r,\ddot{q}_r\right)s \quad (41)$$

Using (40), (39) and inner product (36) with s, a new equation can be written by

$$\begin{aligned} &\frac{1}{2}\frac{d}{dt}\left\{s^T H(q)s + \Delta\mathbf{p}^T\Gamma\Delta\mathbf{p}\right\} \\ &+s^T\left\{M_0 + \zeta\left(\|\dot{x}\|\right)J^T(q)J(q)\right\}s \\ &= s^T J_\varphi^T(q)\left(\xi\lambda - \mu\Delta F\right) - s^T K_d s \\ &= -\eta\left(\mu\Delta F^2 + \frac{1}{2}\frac{d}{dt}\Delta F^2\right) - s^T K_d s \end{aligned} \quad (42)$$

Lyapunove function is selected by

$$V(t) = \frac{1}{2}\left\{s^T H(q)s + \Delta\mathbf{p}^T\Gamma\Delta\mathbf{p} + \eta\Delta F^2\right\} \quad (43)$$

Differentiating (43) and combination with (41), (39), (36) yields

$$\begin{aligned} &\dot{V}(t) = -s^T\left\{M_0 + \zeta\left(\|\dot{x}\|\right)J(q)J^T(q)\right\}s \\ &-\eta\mu\Delta F^2 - s^T K_v s \end{aligned} \quad (44)$$

where, M_0 and K_v are diagonal positive definite matrices, $\zeta\left(\|\dot{x}\|\right)$ is a positive function, η and μ are chosen positive constants. Hence, $\dot{V}(t)$ is negative definite and due to V is positive definite, based on the Lyapunov direct method, the whole system is uniformly stable.

4. Simulation Result

In this section, the adaptive controller using velocity/force observer was simulated by the parameters of the robot A465 of CRS robotics with the six degrees of freedom [19]. The joints 2, 3 and 5 was only employed in this case. In this the simulation, the end-effector of the robot manipulator was controlled to move in a straight line of 0.4m length over plane so that this movement fulfill the constraint. The sample time is given as $T = 1[ms]$. Equation of this line as

$$\varphi(x) = \cos(\omega)y - \sin(\omega)(x - \sigma) \tag{45}$$

the constraint is depicted in Fig. 1

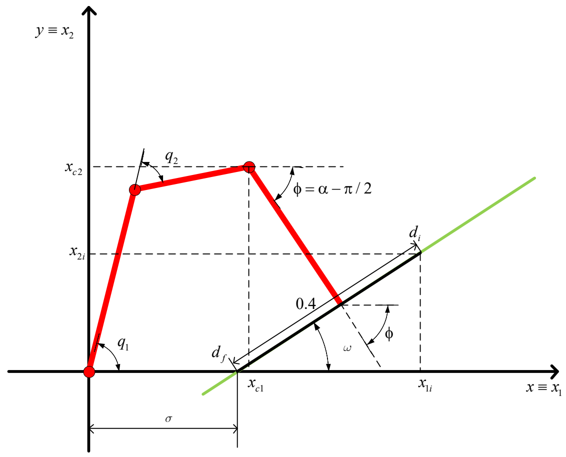

Fig. 1. Constraint of the end-effector

where ω is the inclination of the surface, $\omega = 68[^0]$, σ is the distance between the horizontal axis and flat surface, $\sigma = 0.35[\text{m}]$. The corresponding orientation between the base frame and the end-effector coordinate system is presented by ϕ. The desired orientation is chosen by ϕ_d

$$\phi_d = \phi(0) = \alpha - \pi/2 = -22[^0] \tag{46}$$

The desired force is given as

$$\lambda_d = \begin{cases} 12 + 50(1 - e^{-t/2}) + 15\sin\left(\frac{\pi t}{2}\right), 0 \le t \le 6[s] \\ 60[N] \qquad\qquad\qquad\qquad t \ge 6[s] \end{cases} \tag{47}$$

The simulation results of adaptive position/force controller with using force/ velocity observer are showed in Figs.2-3. In this case, the controller and observer work with a unique position measurement

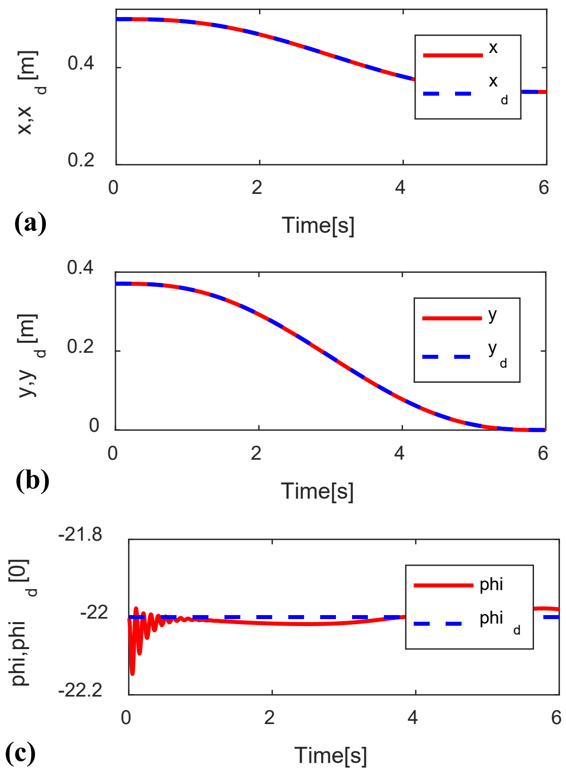

Fig. 2. (a) end-effector position in x-axis, (b) end-effector position in y-axis, (c) orientation of ϕ

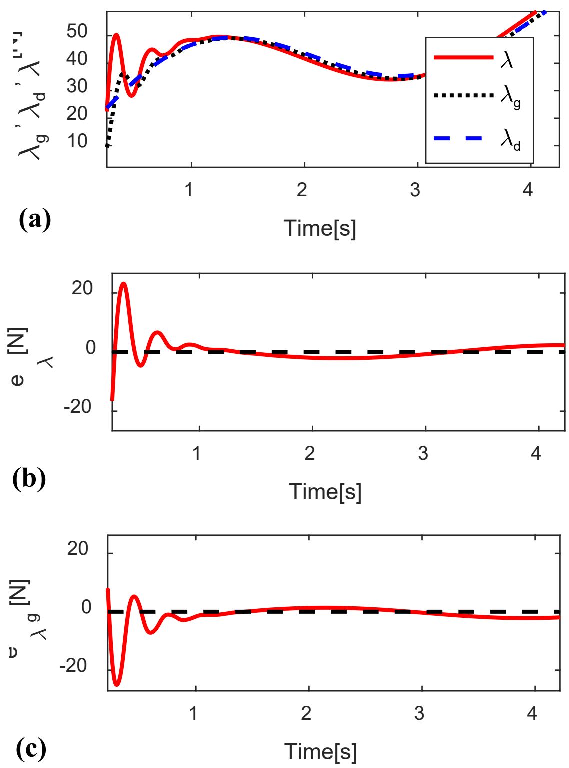

Fig. 3. (a) responding forces, (b) force tracking error, (c) estimated force error

Fig.2 depicts the simulation results of position tracking of the end-effector in Cartesian space that demonstrates good convergence of the real position and the desired position in coordinates x, y and ϕ. Three values of the responding force are presented in Fig. 3 (a). Where, the estimated force is presented by λ_g, the real force and the desired force are denoted by λ and λ_d, respectively Fig.3(b) and Fig.3(c) illustrate errors between the real force and the desired force, between the estimation force and the real force. The results demonstrate a good performance of the convergence with the estimation force and the responding force.

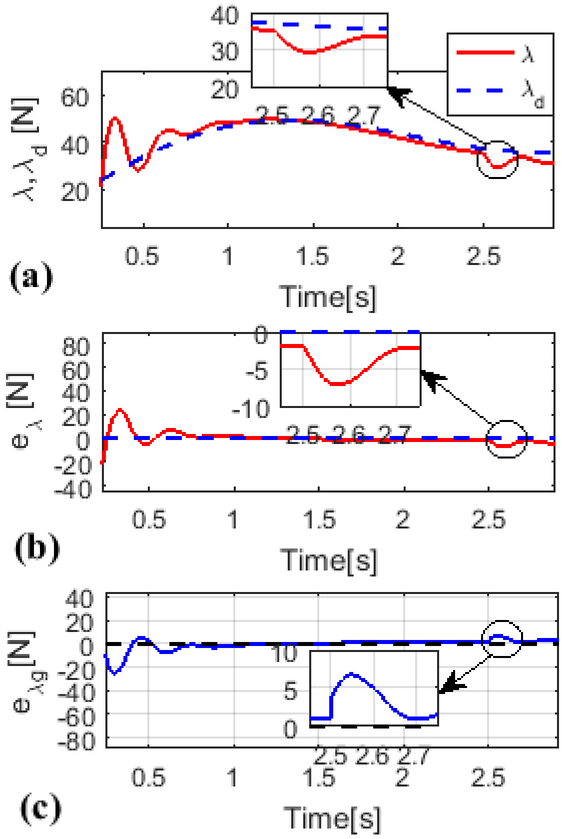

Fig. 4. Responding with the change of parameters at $t = 2.5[s]$: (a) responding force, (b) force tracking error, (c) estimation force error

The next, simulation is performed with the change of parameters of the robot during working. We assume that the change of parameters is made at $t = 2.5[s]$. The change is presented by a vibration of mass or inertia term. ie.,

$p_1, p_3, p_5, p_7, p_9, p_{11}, p_{13}, p_{15}$ are added 5% to its initial values. Similarly

$p_2, p_4, p_6, p_8, p_{10}, p_{12}, p_{14}$ are subtracted 5%, where $\mathbf{p} = [p_1, p_2, ..., p_{15}]^T$ is parameter vector of the robot manipulator. The results are shown in Fig. 4.

In Fig. 4(c), although the change of parameters effects to the responding force but the errors between the real force and the estimated force still tend to zero in the short time.

In Fig. 4(b), the change of parameters will affect the real force. However, these affections will be compensated by the proposed adaptive controller. The parameter vector will be updated continuously by the updating law to adapt with these changes.

5. Conclusion

In this study, an adaptive position/force controller without force and velocity sensors was proposed with only the position measurements. The force and velocity were estimated by the observer. A control algorithm was designed by the development from adaptive control law of E. Slotine. One hand, the combination of the proposed control algorithm and force/velocity observer that be designed by GPI technique dealt with two problems. The first, the velocity and force sensors were absent. The second, there were some parametric uncertainties in the model of the robot. Above proposed observer guaranteed the convergence of velocity and force estimations. On the other hand, the controller has adaptability with the change of parameters when working, such as the changes of payload or inertia torque of robot manipulators.

In the future, this research will be continuously developed by the combination of this force/velocity observer with different controllers, such as GPI controller, sliding mode controller.

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