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On Observer-based Passive Robust Impedance Control of a Robot Manipulator

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Abstract: This paper studies the passive impedance control of a robot manipulator with model uncertainty to perform manipulation tasks while interacting with dynamic environment. Impedance control is a powerful approach for the robot to perform mechanical tasks while interacting with dynamic environment. However, in our previous research, it was clarified that, the time varying impedance center as well as the robot's model uncertainty influences the robot's passivity, which may lead to serious safety problem for both the robot as well as its environment. In order for the robot to keep its passivity as well as to realize desired objective impedance, in this paper, a novel observer based control design is proposed. Computer simulations of a 2-link manipulator interacting with a dynamic wall show the effectiveness of our control approach.

Key words: Passivity, impedance control, model uncertainties.

1. Introduction

This paper studies on the control problem for a robot manipulator to perform mechanical tasks in dynamic environment. Here, the objective of the control design is to realize (1) the robot's tracking in free motion space as well as (2) passivity when the robot is interacting with dynamic environment.

In order for the robot to realize above objectives, Li and Horowitz proposed PVFC (passive velocity field control), which represents the time varying objective trajectory into a form of velocity vector field together with the control strategy using skew symmetric matrixes [1-5]. By adjusting a scaling parameter of the objective velocity vector field, they proved that the robot can realize both tracking and passivity. However, the proposed control design was too complicated to be computed. On the other hand, it is well known that, basically, impedance control proposed by Hogan can keep the robot's passivity when the objective impedance center was constant [6]. However, if the objective impedance center is time varying, that is, if

we require the robot to perform tracking tasks, then, we cannot make sure the robot's passivity. In order for the impedance controlled robot with time varying impedance center to realize passivity, Kishi and Luo et al [7]. proposed a simple switching control approach based on the information of the robot's energy under the condition that the robot does not have any model uncertainty. Following this research, in Ref. [8], we further analyzed the passivity of an impedance controlled robot with model uncertainty. We proposed a unique approach to set the estimation of the robot's dynamics so as to keep the passivity under model uncertainties. However, the influence of robot's model uncertainty on the performance of impedance control was not solved.

In this paper, we propose a novel observer based approach for an impedance controlled robot to compensate the influence from the model uncertainty so as to improve the impedance performance while keeping the robot's passivity. To show the effectiveness of our control approach, we performed computer simulations of a 2-link manipulator interacting with a dynamic wall. It is shown that our approach can greatly improve the robot's impedance performance.

Corresponding author: CAO Sheng, Ph.D., research fields: robot's manipulator control, rehabilitation robot, cable-driven robot.

The paper is organized as following. In Section 2, we formulate the control problem and make review of the existing researches. In Section 3, we propose our observer based passive robust impedance control approach. We give our simulation results in Section 4 and conclude our research in Section 5.

2. Problem Formulation

2.1 Definition of Robot's Passivity

The problem considered in this paper is how to keep the passivity of the robot robustly so as to realize the safety of the robot's movement. The robot's passivity can be interpreted from the perspective of the robot's energy transformation.

Definition 1 [1]*:* A dynamic system with input $u \in U$ and output $y \in Y$ is passive with respect to the supply rate $s: U \times Y \to \Re$ if, for any $u: \Re_+ \to U$ and any $t \geq 0$ the following relationship is satisfied

$$\int_0^t s(u(\gamma), y(\gamma)) d\gamma \geq -c^2 \qquad (1)$$

where, $c \in \Re$ depends on the system's initial conditions.

It is known that, inputs of the mechanical manipulators interacting with the external environment can be divided into two terms, which are control torques (control inputs) τ generated by the actuators and the external forces f_e from the environment, respectively. Meanwhile, joint velocity $\dot{q}$ of the manipulators can be regarded as the outputs of the manipulators. When considering the manipulator which is controlled by a closed loop control algorithm with the feedback controller in the process as in Fig. 1, then the external forces f_e will be regarded as the inputs and manipulators' velocity $\dot{q}$ the outputs of the system [1].

The expression in Eq. (1) states that the energy, which is produced by the robot and applied to the environment, should be limited by c^2 so as to keep the robot' passivity and realize the safety of the robot's movement.
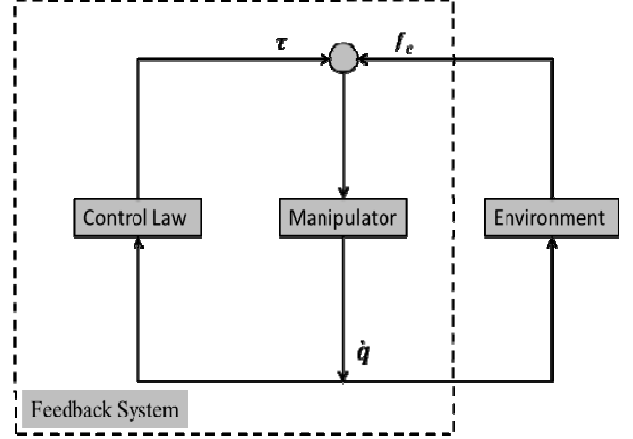

Fig. 1   Robot interacts with the environment and control.

2.2 Dynamics of a Robot

The dynamics of a robot in dynamic environment can be described as:

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} = \tau + J^T f_e \qquad (2)$$

where, $M(q) \in \Re^{n \times n}$ is the inertial matrix, $C(q, \dot{q})\dot{q} \in \Re^{1 \times n}$ is the Coriolis and centrifugal force vector. τ is the applied joint torque and f_e is the interaction forces exerted at the end-effector from the environment. J is the Jacobi matrix from the robot's joint angle q to the work space x.

2.3 Passivity of Impedance Control

In order for the robot to realize the following impedance

$$M_d \ddot{x} + D_d \dot{x} + K_d(x - x_d) = f_e \qquad (3)$$

under the condition that the robot's physical parameters are all known, we can specify the robot's control input as

$$\begin{aligned} \tau = M(q)J^{-1}(q)\{ & M_d^{-1}(-D_d\dot{x} - K_d(x - x_d) \\ & + f_e) - J(\dot{q})\dot{q}\} + C(q, \dot{q})\dot{q} \\ & - J^T f_e \end{aligned} \qquad (4)$$

where, M_d, D_d, K_d are the desired positive mass, damping and stiffness coefficient. $x \in \Re^m$ is the robot's end-effector position, x_d is the impedance center. Mass (M_d) and stiffness (K_d) are energy storing elements, while damper (D_d) possesses the function of dissipating kinetic energy.

From Eq. (3), it is clear that, if the impedance center x_d is constant, then the robot will be passive.

However, if x_d is changing with respect to time, then it will influence the robot's passivity as follows. Here, as in Ref. [7], to analyze the passivity of the robot with impedance control, we define the mechanic energy as

$$E := \frac{1}{2} \dot{x}^T M_d \dot{x} + \frac{1}{2} (x - x_d)^T K_d (x - x_d) \quad (5)$$

It is clear that E is positive. The first and the second term represent the kinetic and potential energy, respectively.

Using Eq. (3), the time change of the mechanic energy can be derived as

$$\frac{d}{dt} E = \dot{x}^T M_d \ddot{x} + (\dot{x} - \dot{x}_d)^T K_d (x - x_d) = \quad (6)$$

$$-\dot{x}^T D_d \dot{x} - \dot{x}_d K_d (x - x_d) + \dot{x}^T f_e$$

By integrating the Eq. (7), we get

$$\int_0^t \dot{x}^T f_e \, ds = E - E|_{t=0}$$

$$+ \int_0^t \left(\dot{x}^T D_d \dot{x} \right.$$
$$+ \dot{x}_d K_d (x - x_d) \right) ds \quad (7)$$
$$\geq -E|_{t=0}$$
$$+ \int_0^t \left(\dot{x}_d K_d (x - x_d) \right) ds$$

From Eq. (7), it is apparent that if x_d do not change with the time variation, that is, if $\dot{x}_d$ is 0, then

$$\int_0^t \dot{x}^T f_e \, ds \geq -E|_{t=0} \quad (8)$$

That is, the energy served by the robot to the environment can be controlled less than the initial kinetic energy so that the surplus energy will not supply to the environment. From the definition of the passivity (i.e. Eq. (1)), the impedance controlled robot is passive.

However, if the impedance center x_d varies with respect to time (i.e. tracking a trajectory), that is, if $\dot{x}_d$ is not 0, then the right side of the Eq. (7) may not satisfy the passivity condition of Eq. (1), which implies that robot may impose surplus energy to environment so as to approach to the desired position as shown in Fig. 2.

2.4 PIC (Passive Impedance Control)

In order to keep the passivity of the robot controlled by impedance control law while performing the trajectory tracking task, it is necessary to appropriately adjust the desired impedance center so as to limit the energy exerted by robot.

In Ref. [7], under the condition that the robot's physical parameters are all known, it was proposed to switch a scaling parameter of the robot's desired velocity as follows. Here, the velocity of the desired impedance center is set as
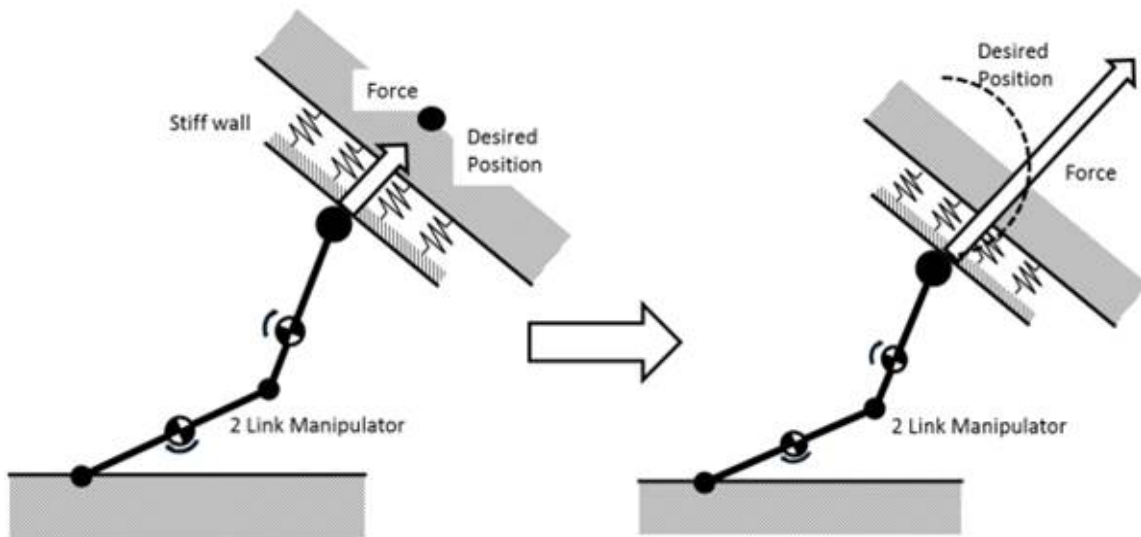

Fig. 2   Comparison between the invariant and varying desired position.

$$\dot{x}_d = \alpha V \tag{9}$$

where, α is the scaling parameter satisfying $\alpha > 0$, V was defined as the tangent velocity vector of impedance center trajectory designed previously without considering the environmental uncertainties.

Then, if we adjust the scaling parameter α satisfying the condition

$$\alpha \begin{cases} \leq -\dfrac{\gamma S + \dot{x}^T D_d \dot{x}}{z} \ when \ z < 0 \\ \geq -\dfrac{\gamma S + \dot{x}^T D_d \dot{x}}{z} \ when \ z > 0 \end{cases} \tag{10}$$

the robot would be passive. Here, γ is a positive value and a new value z was defined as

$$z := V^T K_d (x - x_d) \tag{11}$$

To understand this control approach, let's define a new value S, or accurate to say, the derivative of S as

$$\dot{S} := \dot{x}^T D_d \dot{x} + \dot{x}_d K_d (x - x_d) \tag{12}$$

where the initial value of S has been set as $S_0 > 0$.

From Eq. (12), if we make

$$\dot{S} \geq -\gamma S \tag{13}$$

since the initial value of S is set as $S_0 > 0$, we have

$$S > S_0 e^{-\gamma t} > 0 \quad \forall t > 0$$

Base on this setting, α's condition can be derived as Eq. (10). and one possible choice of α can be given as

$$\alpha = (\gamma S + \dot{x}^T D_d \dot{x})(1 + \dfrac{1 - e^{-cz}}{1 + e^{-cz}}) \tag{14}$$

Therefore, from Eqs. (6) and (12), we get

$$\dfrac{d}{dt}(E + S) = \dot{x}^T f_e \tag{15}$$

Since $S > 0$, Eq. (7) becomes

$$\int_0^t \dot{x}^T f_e \, ds = E + S - (E_0 + S_0) \\ > -(E_0 + S_0) \tag{16}$$

Thus, energy served to the environment can be limited by $E_0 + S_0$ so that the impedance controlled robot remains passive.

2.5 Influences of Model Uncertainties for Passive Impedance Control

Here, we further consider the case that the robot's

dynamics M and C are unknown. We set their estimations as $\widehat{M}$ and $\widehat{C}$, respectively. We also define $\widetilde{M}$ and $\widetilde{C}$ as error terms as

$$\widetilde{M} := M - \widehat{M}, \widetilde{C} := C - \widehat{C}.$$

Then, from Eq. (5), now the robot's control input becomes

$$\tau = \widehat{M}J^{-1}(q)\{M_d^{-1}(-D_d\dot{x} - K_d(x - x_d) \\ + f_e) - J(q)\dot{q}\} + \widehat{C}\dot{q} - J^T f_e \tag{17}$$

Put this control into Eq. (2), then we get

$$M_d\ddot{x} + D_d\dot{x} + K_d(x - x_d) = f_e + f_m \tag{18}$$

where, f_e is the external force while f_m represents the force term caused by the robot's model uncertainties as

$$f_m := -(M_d J \widehat{M}^{-1}\widetilde{M}\ddot{q} + M_d J \widehat{M}^{-1}\widetilde{C}\dot{q}) \tag{19}$$

From Eq. (19), it is clear that model errors actually may have effects on the results of impedance control and the passivity of the robot as follows:

$$\int_0^t \dot{x}^T f_e \, ds = E + S - (E_0 + S_0) \\ - \int_0^t \dot{x}^T f_m \, ds \tag{20}$$

Since the term $\int_0^t (-\dot{x}^T f_m)ds$ exists, besides of time-varying impedance center, the robot's model uncertainties also influence the change of the energy which is provided by the robot to the environment. Therefore, robot may lose its passivity even under the control frame of passive impedance control method.

In our previous study of Ref. [8], we proposed an approach to select the estimation of M and C so as the robot can keep its passivity under the model uncertainties. However, the performance of impedance control still is influenced by the model error term f_m and thus remains to be improved.

3. Passive Robust Impedance Control

In this section, we propose a novel observer based passive robust impedance control approach which designs an observer to detect the model error f_m so as to decrease the effect of the term $\int_0^t \dot{x}^T f_m \, ds$ in

Eq. (20) to make the robot passive as well as realize the robot's impedance control performance.

By introducing f_c as a new input force, we select the robot's control law as

$$\boldsymbol{\tau}' = \widehat{M}(q)J^{-1}(q)\{M_d{}^{-1}(-D_d\dot{x} - K_d(x - x_d)$$
$$+ f_e + f_c) - \dot{J}(q)\dot{q}\} \qquad (21)$$
$$+ \widehat{C}(q, \dot{q})\dot{q} - J^T f_e$$

f_c is mainly designed to eliminate the model error force f_m in the impedance equation which will be shown later.

By applying this control input, the robot's impedance becomes:

$$M_d\ddot{x} + D_d\dot{x} + K_d(x - x_d) = f_e + f_c + f_m \quad (22)$$

On the other hand, we also introduce a new reference x_r and set the ideal impedance as

$$M_d\ddot{x}_r + D_d\dot{x}_r + K_d(x_r - x_d) = f_e \qquad (23)$$

where, $\ddot{x}_r$, $\dot{x}_r$ and x_r represent the robot's ideal acceleration, velocity and position, respectively.

By calculating Eqs. (22) and (23), we can obtain

$$M_d\ddot{x}_e + D_d\dot{x}_e + K_dx_e = f_c + f_m \qquad (24)$$

where, $x_e := x - x_r$.

Since the robot's real position x as well as the interaction force f_e from the environment to the robot can all directly be measured, then we can obtain x_r from Eq. (23) and in turn, the error position x_e. By filtering this error position x_e using the following transfer function:

$$O(s) = \frac{M_ds^2 + D_ds + K_d}{Ts^2 + bs} \qquad (25)$$

then we can design the new control force

$$f_c = -O(s)Ix_e \qquad (26)$$

so that

$$f_c = \frac{-1}{Ts^2 + bs + 1}If_m.$$

By setting the parameters T and b, we can make sure that $f_c + f_m \to 0$. Therefore, the robot's model error will not influence the impedance control of Eq. (22). Here, I is an unit matrix. The overall observer design is shown in Fig. 3.
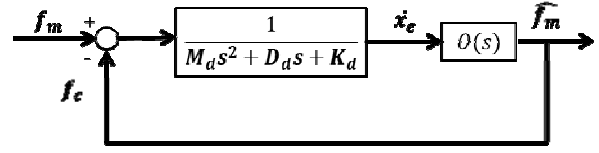

Fig. 3   Block diagram of the disturbance observer design.

4. Simulation Studies

4.1 Simulation Settings

In order to verify the effectiveness of our robust passive impedance control method, we performed computer simulations, which consider a 2 D.O.F robot arm interacting with an unknown stiff wall as shown in Fig. 4. Here, we set the initial desired trajectory of the impedance center as a circular motion.

All physical parameters of the robot in Fig. 5 used for simulation are listed in Table 1.

We mainly performed simulation for four different conditions as follows, respectively:

(1) There are no model errors, and the robot is controlled by passive impedance control method.

(2) There are model errors, and the robot is controlled by the same passive impedance control method as in (1).The estimated mass and center of the link's gravity, which are used in the calculation of the estimated inertial matrix, is set as

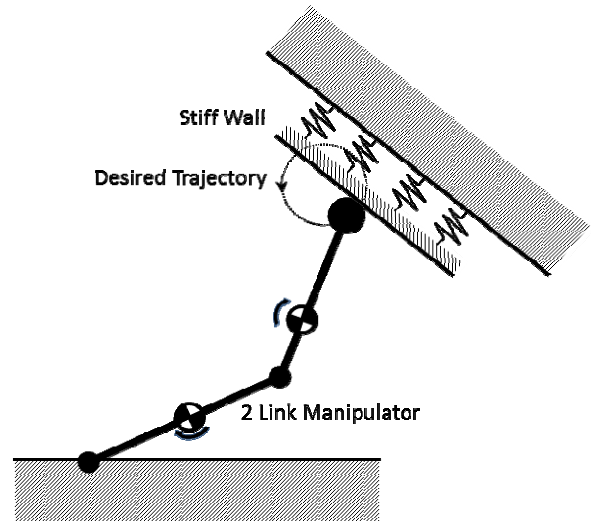$$\widehat{m_i} = 0.5 \times m_i. \widehat{lg_i} = 0.5 \times lg_i$$

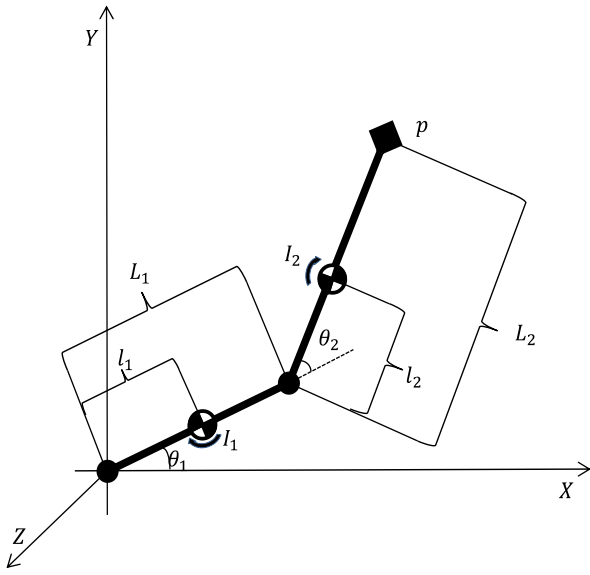Fig. 4   Simulations of a 2 D.O.F robot arm moving on a dynamic wall.

Fig. 5 Physical parameters of a 2 D.O.F robot.

Table 1 Simulation parameters of the robot.

I_1	0.3125	kgm^2
I_2	0.3125	kgm^2
m_1	5	Kg
m_2	5	Kg
l_1	0.25	M
l_2	0.25	M
L_1	0.5	M
L_2	0.5	M

where, m represents the mass of the link and lg represents the position of the center of the gravity of the link.

(3) There are model errors, and the control method is as we proposed in research [8], which keeps the robot's passivity.

(4) There are model errors, and the control method is our observer-based passive impedance control.

In addition, we also set the parameter in the matrix K_d, D_d and M_d of the impedance equation as

$$M_d = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} D_d = \begin{bmatrix} 2 & 0 \\ 0 & 2 \end{bmatrix} K_d = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

and the parameter in the matrix K_e and K_e of the stiff wall as $k_e = 15$, $d_e = 1$. The initial value of S and the mechanic energy E has been defined as $S_0 = 0.5$ J, $E_0 = 0$ J.

The parameter in observer is set as T = 0.0001, b = 0.02.

4.2 Simulation Results

4.2.1 Effects of the Impedance Control Method in Different Cases

The blue line denotes the results of the case (1). The orange line and the red dot line represent the results of the cases (2) and (3), and the black dot lines are the results of the case (4).

The trajectory tracking results of four cases are shown in Fig. 6. The grey line shown in this figure represents the stiff wall whose spring and damping ratio are set as $k_e = 15$ and $d_e = 3$ respectively.

As seen from the trajectory of the orange line in Fig. 6, we can find that the robot's model errors seriously influence the tracking ability of the robot. The trajectory of the red line shows that the method proposed in Ref. [8] does not contribute to the performance of trajectory tracking. From the trajectory tracking results of the black dot line and the blue line in Fig. 6, it is clear that, by utilizing our method, the effects of the model error on the trajectory tracking can be eliminated.

Figs. 7 and 8 show the errors between the real value of the robot's position and velocity in task space and the ideal value when there exists no model error in control system. From these results, it is obvious that the observer-based method can effectively decrease the tracking errors caused by the model errors, which are even better than the results of our previous research [8] in case (3).
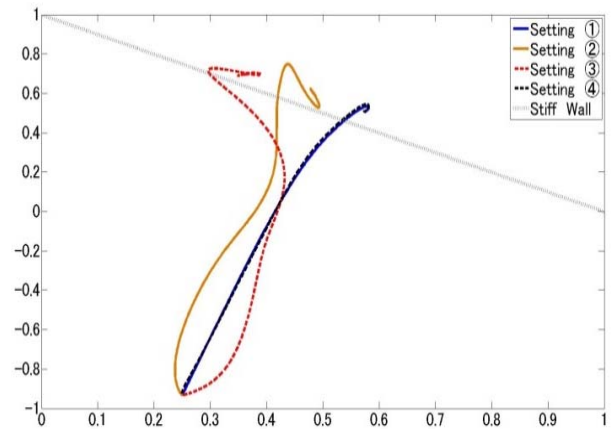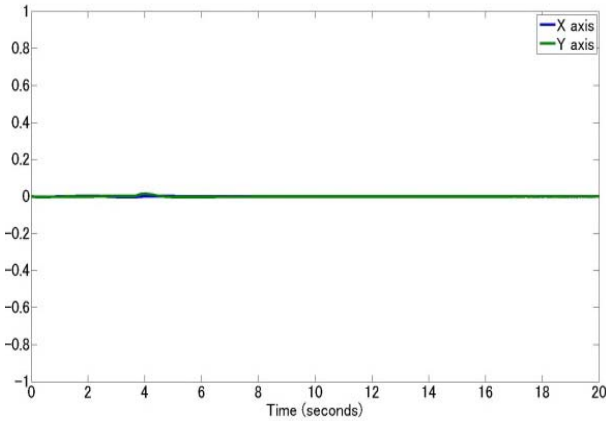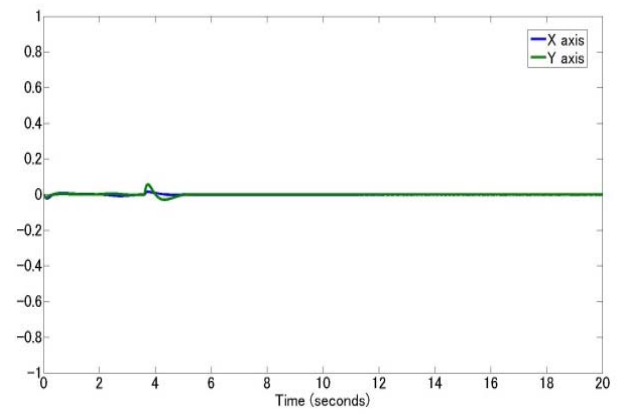

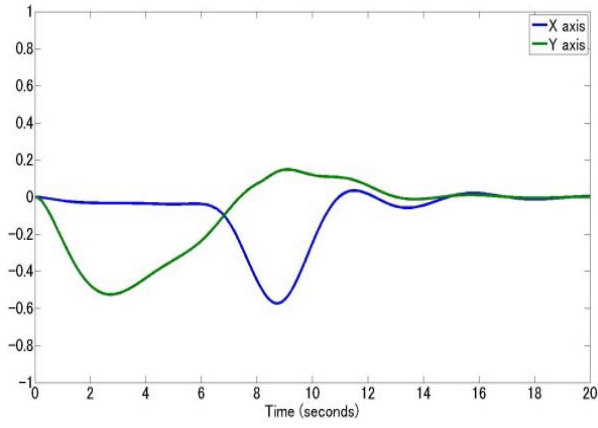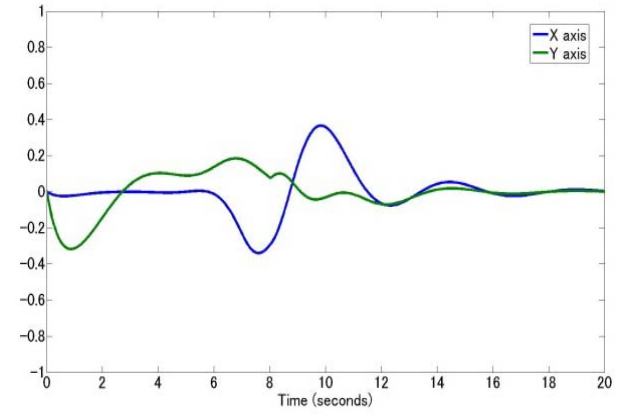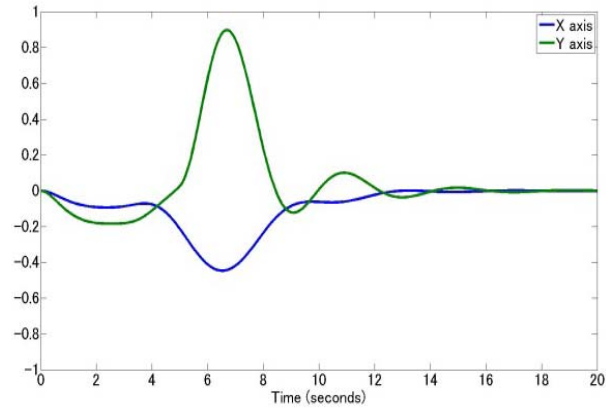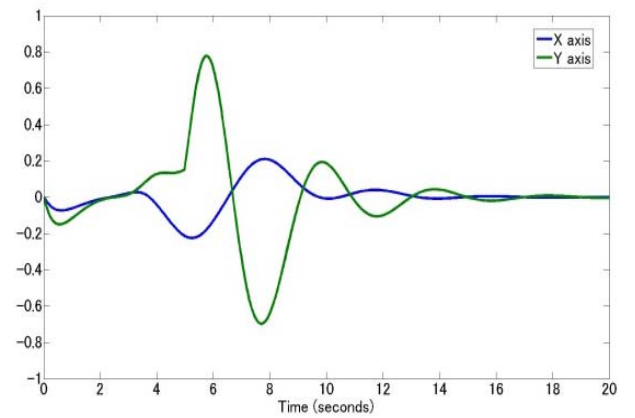**Fig. 6 Trajectory of the robot in four different cases.**

(a) Time responses of position errors x_e in case (4)

(a) Time responses of velocity errors $\dot{x}_e$ in case (4)

(b) Time responses of position errors x_e in case (3)

(b) Time responses of velocity errors $\dot{x}_e$ in case (3)

(c) Time responses of position errors x_e in case (2)

(c) Time responses of velocity errors $\dot{x}_e$ in case (2)

Fig. 7   Time responses of position errors x_e in different cases.

Fig. 8   Time responses of velocity errors $\dot{x}_e$ in different cases.

Fig. 9 shows the response of external forces in four different cases. It is clear that model errors may have some effects on the response time and the vibration of the force. Also, it is shown that the observer-based controller can lead the external force to approach the ideal value.

From Figs. 6 to 9, it is found that the previous method (3) could not decrease the effect from the model errors on impedance control law and observer-based method could eliminate this effect and help the robot to realize the ideal impedance.
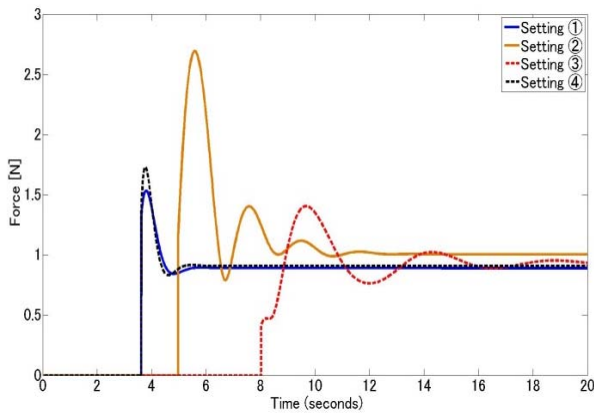
Fig. 9   The external force responses of the robot in four different cases.
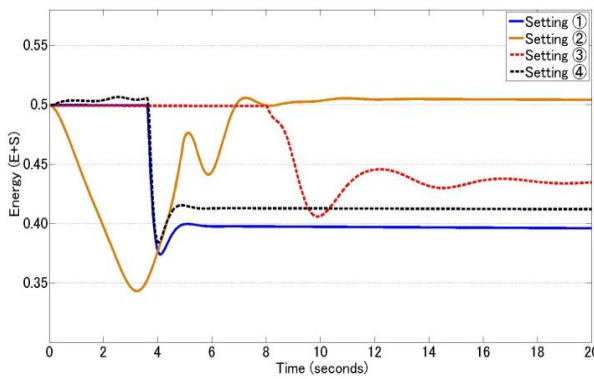

Fig. 10   The energy (E+S) in four different cases.

4.2.2 Passivity Analysis

Fig. 10 shows the energy results of E+S in different cases. The orange line shows that model errors could affect the energy's variation so as to make the energy (E+S) exceed the its initial value 0.5 J, which means that the robot is not passive. By using the previous method [8] with a special estimation adjustment, from red dot line, we see that the passivity can be satisfied. The black dot line shows that the robot is passive by using our proposed observer-based method. By comparing the black dot line and the orange line, we see that our proposed controller could effectively decrease the influence of model errors on the energy E+S, therefore, the robot can keep its passivity under the model errors.

5. Conclusions

This paper proposed a novel control approach for a robot with model uncertainties to perform dynamic interaction with environment. By introducing a reference impedance model as well as an observer, this approach can not only keep the robot's passivity even for the time-varying impedance center, but also greatly improve the impedance control performances such as tracking responses. Computer simulations of a 2 D.O.F robot arm interacting with a stiff environment show the effectiveness of our approach.

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