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

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Abstract: Passivity is an important requirement for a robot to interact with human or other dynamic environments stably and safely as in robotic rehabilitations. Considering the time-varying objective impedance center, under the condition that the robot's dynamics is known, previous research has already proposed a passive impedance control approach which adjusts a scaling parameter of the robot's desired velocity with respect to the robot's mechanic energy so as to maintain the robot's passivity. In this research, we furture take into account of the robot's dynamical model uncertainties and propose a robust passive impedance control. Computer simulations of a 2-link manipulator interacting with a dynamic wall show the effectiveness of our robust control approach.

Key words: Passivity, impedance control, model uncertainties.

1. Introduction

This research proposes a novel robust passive impedance control for a robot manipulator which has dynamic model uncertainties to interact with its dynamic environment stably and safely.

To realize the physical environmental interactive tasks by a robot, so far many force control approaches have been proposed [1]. Recently, in order to remain the robot's passivity as seen from the environment, the PVFC (passive velocity field control) as well as PIC (passive impedance control) considering time-varying impedance center has been presented [2, 3]. The adaptive PVFC has also been studied by considering the robot's dynamic model error, which has been applied in exercise machine [4, 5]. It is also well known that, for the position tracking control of a robot manipulator, the robust tracking control approach has been proposed [6] and the approach to keep the passivity of this robust tracking control has also been published in Ref. [7].

In this research, we analyze the influences caused by dynamic model uncertainties of a robot on its passivity when applying PIC. By adjusting estimations of the robot's parameter with respect to the robot's mechanic energy, we propose our RPIC (robust passive impedance control) approach. Computer simulations have also been performed to show the effectiveness of our approach.

The paper is organized as following: In Section II, we define the robot system's passivity and describe the problem formulation. Section III analyzes the influence of the robot's model uncertainties to the passivity of the impedance control, followed by propose of our robust passive impedance control approach in Section IV. In Section V, we give our simulation results and conclude our research in Section VI.

2. Problem Formulation

2.1 Dynamics of Robot Interacting with Environment

The dynamics of a robot in dynamic environment are usually described as:

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

where $\mathbf{M}(\mathbf{q}) \in \Re^{n\times n}$ is the inertial matrix, $\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} \in \Re^{1\times n}$ is the Coriolis and centrifugal force vector. $\boldsymbol{\tau}$ is the applied joint torque and $\mathbf{f}_{\mathrm{e}}$ is the interaction forces exerted at the end-effector. $\mathbf{J}$ is the

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Jacobi matrix from the robot's joint angle $\mathbf{q}$ to the work space $\mathbf{x}$.

Impedance Control: By specifying the control input to Eq. (1) as

$$\begin{aligned}\boldsymbol{\tau} = \mathbf{M}(\mathbf{q})\mathbf{J}^{-1}(\mathbf{q})\{\mathbf{M_d}^{-1}(-\mathbf{D_d}\dot{\mathbf{x}} - \mathbf{K_d}(\mathbf{x} - \mathbf{x_d}) \\ + \mathbf{f_e}) - \mathbf{J}(\dot{\mathbf{q}})\dot{\mathbf{q}}\} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} \\ - \mathbf{J}^{\mathbf{T}}\mathbf{f_e}\end{aligned} \quad (2)$$

then the robot's mechanical impedance as seen from the environment becomes

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

where, $\mathbf{M_d}, \mathbf{D_d}, \mathbf{K_d}$ are the desired positive inertia, damping and stiffness of the robot. $\mathbf{x} \in \Re^m$ is the robot's end-effector position, $\mathbf{x_d}$ is the desired impedance center of the robot in the work space.

Passivity of Impedance Control: As in Ref. [3], to analyze the passivity of the robot with impedance control, we define the mechanic energy as

$$E := \frac{1}{2}\dot{\mathbf{x}}^{\mathbf{T}}\mathbf{M_d}\dot{\mathbf{x}} + \frac{1}{2}(\mathbf{x} - \mathbf{x_d})^{\mathbf{T}}\mathbf{K_d}(\mathbf{x} - \mathbf{x_d}) \quad (4)$$

which is positive. The first and second term represent kinetic and potential energy, respectively.

The time change of the mechanic energy can be derived as using Eq. (3).

$$\begin{aligned}\frac{d}{dt}E = \dot{\mathbf{x}}^{\mathbf{T}}\mathbf{M_d}\ddot{\mathbf{x}} + (\dot{\mathbf{x}} - \dot{\mathbf{x_d}})^{\mathbf{T}}\mathbf{K_d}(\mathbf{x} - \mathbf{x_d}) \\ = -\dot{\mathbf{x}}^{\mathbf{T}}\mathbf{D_d}\dot{\mathbf{x}} - \dot{\mathbf{x_d}}\mathbf{K_d}(\mathbf{x} - \mathbf{x_d}) \\ + \dot{\mathbf{x}}^{\mathbf{T}}\mathbf{f_e}\end{aligned} \quad (5)$$

Then, from Eq. (5), the energy which comes from the environment is

$$\begin{aligned}\int_0^t \dot{\mathbf{x}}^{\mathbf{T}}\mathbf{f_e}\,ds = E - E|_{t=0} \\ + \int_0^t \left(\dot{\mathbf{x}}^{\mathbf{T}}\mathbf{D_d}\dot{\mathbf{x}} \right. \\ \left. + \dot{\mathbf{x_d}}\mathbf{K_d}(\mathbf{x} - \mathbf{x_d})\right) ds \\ \geq -E|_{t=0} \\ + \int_0^t \left(\dot{\mathbf{x_d}}\mathbf{K_d}(\mathbf{x} - \mathbf{x_d})\right) ds\end{aligned} \quad (6)$$

From Eq. (6), it is clear that if $\mathbf{x_d}$ does not change with time, that is, $\dot{\mathbf{x_d}}$ is 0, then

$$\int_0^t \dot{\mathbf{x}}^{\mathbf{T}}\mathbf{f_e}\,ds \geq -E|_{t=0} \quad (7)$$

That is, the impedance controlled robot is passive.

However, if the impedance center $\mathbf{x_d}$ varies with time, that is, $\dot{\mathbf{x_d}}$ is not 0, the robot will impose surplus energy to environment with $\mathbf{x_d}$'s change and it is then difficult to guarantee the robot system's passivity.

PIC (Passive Impedance Control): In order to keep the passivity of the impedance controlled robot (PIC) even if the desired impedance center is time-varying, in Ref. [3], it proposed an approach to switch a scaling parameter of the robot's desired velocity as following. Here, the velocity of the impedance center is set as

$$\dot{\mathbf{x_d}} = \alpha\mathbf{V} \quad (8)$$

with the scaling parameter $\alpha > 0$, which will be defined later. By defining a new value z as

$$z := \mathbf{V}^{\mathbf{T}}\mathbf{K_d}(\mathbf{x} - \mathbf{x_d}) \quad (9)$$

and another value S, or accurate to say, the derivative of S as

$$\dot{S} := \dot{\mathbf{x}}^{\mathbf{T}}\mathbf{D_d}\dot{\mathbf{x}} + \dot{\mathbf{x_d}}\mathbf{K_d}(\mathbf{x} - \mathbf{x_d}) \quad (10)$$

where the initial value of $\mathbf{S}$ will be set as $S_0 > 0$. Then if we adjust the scaling parameter α as

$$\alpha\begin{cases}\leq -\dfrac{\gamma S + \dot{\mathbf{x}}^{\mathbf{T}}\mathbf{D_d}\dot{\mathbf{x}}}{z} & \text{when } z < 0 \\ \geq -\dfrac{\gamma S + \dot{\mathbf{x}}^{\mathbf{T}}\mathbf{D_d}\dot{\mathbf{x}}}{z} & \text{when } z > 0\end{cases} \quad (11)$$

we get $\dot{S} \geq -\gamma S$. Then we have $S > S_0 e^{-\gamma t} > 0\ \forall t > 0$.

Note that Eqs. (8) and (11) implied that when the value of $\dot{S}$ changes, it is necessary to adjust the value of the α simultaneously to make $S > 0$. Here, one possible choice of $\boldsymbol{\alpha}$ is given as

$$\alpha = (\gamma S + \dot{\mathbf{x}}^{\mathbf{T}}\mathbf{D_d}\dot{\mathbf{x}})(1 + \frac{1 - e^{-cz}}{1 + e^{-cz}}) \quad (12)$$

Therefore, from Eq. (5) and (10), we get $\frac{d}{dt}(E + S) = \dot{\mathbf{x}}^{\mathbf{T}}\mathbf{f_e}$,

$$\int_0^t \dot{\mathbf{x}}^{\mathbf{T}}\mathbf{f_e}\,ds = E + S - (E_0 + S_0) > -(E_0 + S_0) \quad (13)$$

The impedance controlled robot remains passive. As shown in Eq. (2), here the robot's dynamic model uncertainties were not considered. If there are such uncertainties, then the robot's passivity will also be influenced. Therefore, in the following two sections, we first analyze the influence comes from the robot's model uncertainties and then propose our robust passive impedance control.

3. Influences of Model Uncertainties under Passive Impedance Control

Here, we assume that the robot's dynamics $\mathbf{M}$ and $\mathbf{C}$ are unknown and their estimations are $\widehat{\mathbf{M}}$ and $\widehat{\mathbf{C}}$, respectively. We also define $\widetilde{\mathbf{M}}$ and $\widetilde{\mathbf{C}}$ as model errors, that is $\widetilde{\mathbf{M}} := \mathbf{M} - \widehat{\mathbf{M}}, \widetilde{\mathbf{C}} := \mathbf{C} - \widehat{\mathbf{C}}$.

Then, with respect to Eq. (2), now the robot's control input becomes

$$\boldsymbol{\tau} = \widehat{\mathbf{M}}\mathbf{J}^{-1}(\mathbf{q})\{\mathbf{M_d}^{-1}(-\mathbf{D_d}\dot{\mathbf{x}} - \mathbf{K_d}(\mathbf{x} - \mathbf{x_d}) + \mathbf{f_e}) - \dot{\mathbf{J}}(\mathbf{q})\dot{\mathbf{q}}\} + \widehat{\mathbf{C}}\dot{\mathbf{q}} - \mathbf{J^T f_e} \quad (14)$$

Put this control to Eq. (1), then we get

$$\mathbf{M_d}\ddot{\mathbf{x}} + \mathbf{D_d}\dot{\mathbf{x}} + \mathbf{K_d}(\mathbf{x} - \mathbf{x_d}) = \mathbf{f_e} + \mathbf{f_m} \quad (15)$$

where $\mathbf{f_e}$ is the external force while $\mathbf{f_m}$ represents the force term caused by the robot's model uncertainties as

$$\mathbf{f_m} := -(\mathbf{M_d}\mathbf{J}\widehat{\mathbf{M}}^{-1}\widetilde{\mathbf{M}}\ddot{\mathbf{q}} + \mathbf{M_d}\mathbf{J}\widehat{\mathbf{M}}^{-1}\widetilde{\mathbf{C}}\dot{\mathbf{q}}) \quad (16)$$

For the same energy analysis for Eq. (4) and (10), we then have

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

That is, beside of time-varying impedance center, the robot's model uncertainties also influence its passivity.

4. RPIC (Robust Passive Impedance Control)

In this section, we propose a novel robust control approach so as to keep the robot's passivity during impedance control even if there are model uncertainties of the robot.

Considering the robot's model error term of f_m, here we set the new energy as

$$E = \frac{1}{2}\dot{\mathbf{x}}^{\mathbf{T}}\mathbf{M_d}\dot{\mathbf{x}} + \frac{1}{2}(\mathbf{x} - \mathbf{x_d})^{\mathbf{T}}\mathbf{K_d}(\mathbf{x} - \mathbf{x_d}) + E_m \quad (17)$$

where $E_m = \frac{1}{2}\dot{\mathbf{q}}^{\mathbf{T}}\widetilde{\mathbf{M}}\dot{\mathbf{q}}$. Note, it is necessary to keep E_m positive, therefore we have to carefully select the estimation $\widehat{M}$ so that $\widetilde{M}$ can always be positive definite matrix. In this paper, we select $\widehat{\mathbf{M}} := \mathbf{J^T M_d J}, \widehat{\mathbf{C}} = \frac{1}{2}\dot{\widehat{\mathbf{M}}} = \mathbf{J}^T\mathbf{M_d}\dot{\mathbf{J}}$ and set small $\mathbf{M_d}$ so that $\widetilde{\mathbf{M}} := \mathbf{M} - \widehat{\mathbf{M}}$ can be positive definite.

Then, the time variation of the energy can now be obtained as

$$\frac{d}{dt}E = -\dot{\mathbf{x}}^{\mathbf{T}}\mathbf{D_d}\dot{\mathbf{x}} - \dot{\mathbf{x_d}}\mathbf{K_d}(\mathbf{x} - \mathbf{x_d}) + \dot{\mathbf{x}}^{\mathbf{T}}\mathbf{f_e} + \dot{W}_m \quad (18)$$

With $\dot{W}_m = \dot{\mathbf{x}}^{\mathbf{T}}\mathbf{f_m} + \dot{E}_m = -\dot{\mathbf{x}}^{\mathbf{T}}(\mathbf{M_d}\mathbf{J}\widehat{\mathbf{M}}^{-1}\widetilde{\mathbf{M}}\ddot{\mathbf{q}} + \mathbf{M_d}\mathbf{J}\widehat{\mathbf{M}}^{-1}\widetilde{\mathbf{C}}\dot{\mathbf{q}}) + \dot{\mathbf{q}}^{\mathbf{T}}(\widetilde{\mathbf{M}}\ddot{\mathbf{q}} + \widetilde{\mathbf{C}}\dot{\mathbf{q}}) = 0$. The time variation of energy now becomes

$$\frac{d}{dt}E = -\dot{\mathbf{x}}^{\mathbf{T}}\mathbf{D_d}\dot{\mathbf{x}} - \dot{\mathbf{x_d}}\mathbf{K_d}(\mathbf{x} - \mathbf{x_d}) + \dot{\mathbf{x}}^{\mathbf{T}}\mathbf{f_e} \quad (19)$$

Then, by using the same passive impedance control in Section II, we can keep the robot's passivity.

And by substituting of $\widehat{\mathbf{M}} := \mathbf{J^T M_d J}, \widehat{\mathbf{C}} = \frac{1}{2}\dot{\widehat{\mathbf{M}}} = \mathbf{J}^T\mathbf{M_d}\dot{\mathbf{J}}$ into the control input Eq. (14), τ becomes

$$\boldsymbol{\tau} = -\mathbf{J^T}(\mathbf{D_d}\dot{\mathbf{x}} + \mathbf{K_d}(\mathbf{x} - \mathbf{x_d})) - \mathbf{J^T f_e} \quad (20)$$

This is a very smart and simple PD (proportional–derivative) like control+force feedback which is even simple that the original control of Eq. (2) has nonlinear feedback compensation using the robot's dynamic parameters of $\mathbf{M}$ and $\mathbf{C}$. The only condition here is that we have to set small $\mathbf{M_d}$ so $\widehat{\mathbf{M}} := \mathbf{J^T M_d J}$ can make $\widetilde{\mathbf{M}} := \mathbf{M} - \widehat{\mathbf{M}}$ be positive definite as well as $\widehat{\mathbf{C}} = \frac{1}{2}\dot{\widehat{\mathbf{M}}} = \mathbf{J}^T\mathbf{M_d}\dot{\mathbf{J}}$.

5. Simulation Studies

We perform computer simulations to show the effectiveness of our robust passive impedance control. Consider a 2 D.O.F robot arm interacting with an unknown stiff wall as shown in Fig. 1.

The robot's all physical parameters used for simulation are listed in Table 1. Here, we mainly performed three types of simulations. The first type and the second type use same previous passive impedance control, but in different cases: (1) when there is no model error $\widehat{m_i} = 1.0 \times m_i$ and (2) when

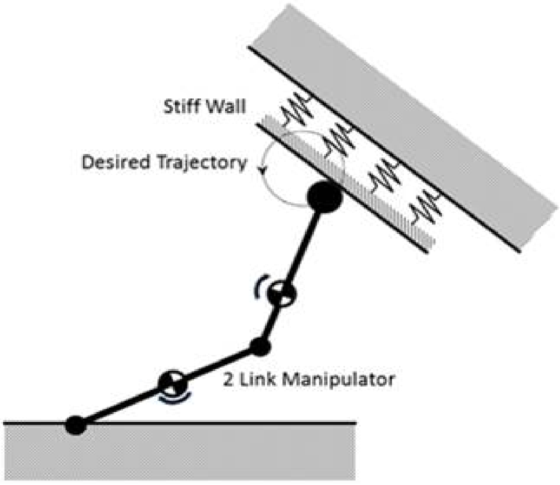

Fig. 1 Computer simulations of a 2 D.O.F robot arm moving on a dynamic wall.

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

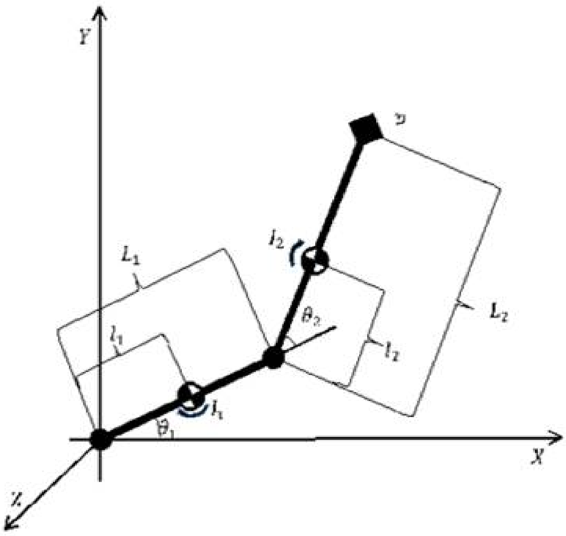

Fig. 2 Physical parameters of a 2 D.O.F robot.

the estimated $\widehat{m_i} = 1.8 \times m_i$. The third type uses our robust passive impedance control method when the estimated inertial matrix $\widehat{\mathbf{M}} = \mathbf{J}^{\mathbf{T}}\mathbf{M}_{\mathbf{d}}\mathbf{J}$ and the estimated Coriolis and centrifugal force term of $\widehat{\mathbf{C}} = \mathbf{J}^{\mathbf{T}}\mathbf{M}_{\mathbf{d}}\dot{\mathbf{J}}$.

In addition, we also set the parameter in the matrix (K_d, D_d, M_d) of the impedance equation and the parameter in the matrix (K_e, D_e) of the stiff wall as $k_d = 25,\ d_d = 10,\ m_d = 1$ and $k_e = 375,\ d_e = 200$. The initial value of S has been defined as $S_0 = 0.02$. Considering the initial value of mechanic energy E_0 is 0, the value $E_0 + S_0$ is 0.02.

Figs. 3 to 5 show the result using passive impedance control on robot without model errors, while Figs. 6 to 8 are for the case when we set $\widehat{m_i} = 1.8 \times m_i$, and Figs. 9 to 11 are results of our robust passive impedance control. From Fig. 3, We can see that the external force converges to the value of 1 N after the contact. Fig. 4 shows the time change of the mechanic energy of the robot, it is clear that the energy did not exceed the initial value $E_0 + S_0 = 0.02$, the robot can keep the passivity by using PIC method.

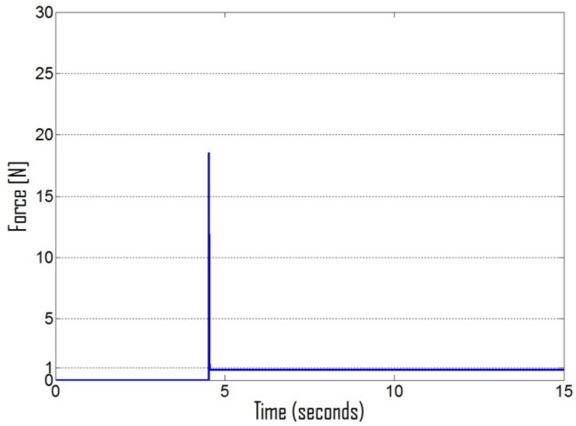

Fig. 3 The contact force by PIC with real inertial parameter.

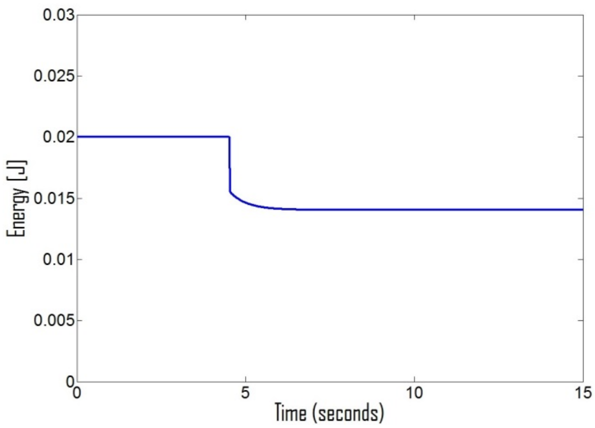

Fig. 4 The mechanic energy by PIC with real inertial parameter.

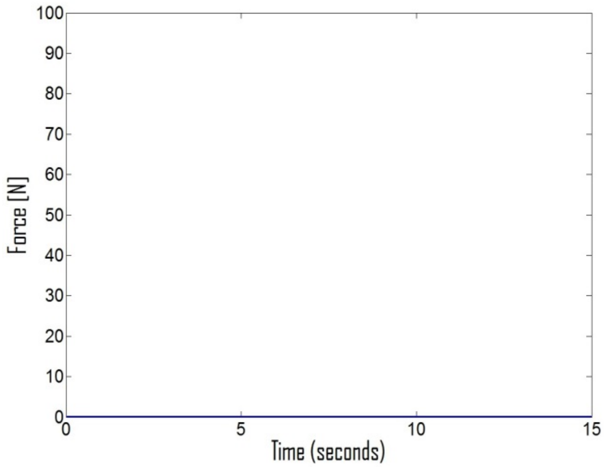

Fig. 5 f_m by PIC with real inertial parameter.

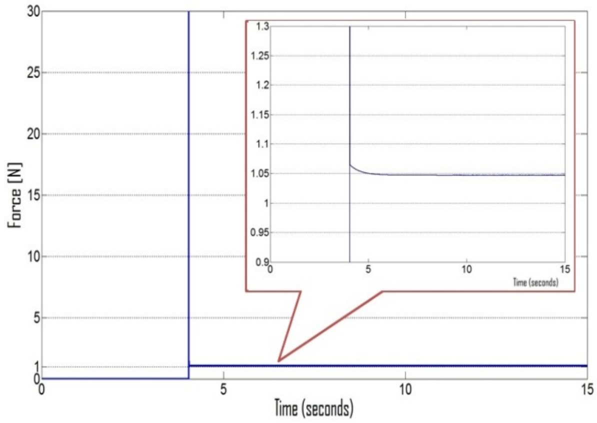

Fig. 6 The contact force by PIC with Estimate inertial = 1.8 × real inertial parameter.

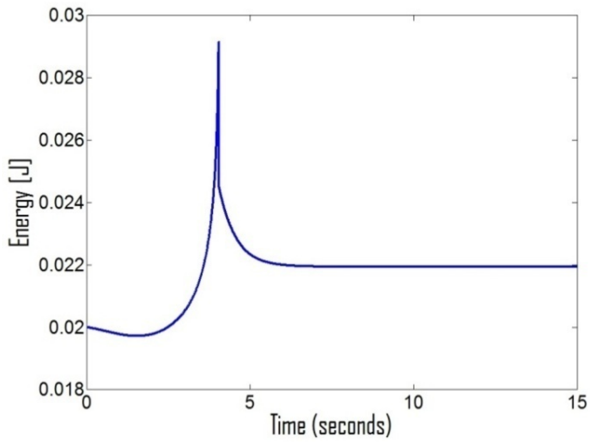

Fig. 7 The mechanic energy by PIC with Estimate inertial = 1.8 × real inertial parameter.

When there are model errors, from Fig. 6, the external forces exceed the line of 1 N when and after the end-effector punches the wall. From Fig. 7, the mechanic energy always exceeds over the initial energy of 0.02 J. And, from Eq. (13), the robot lost its passivity when interacting with the environment.

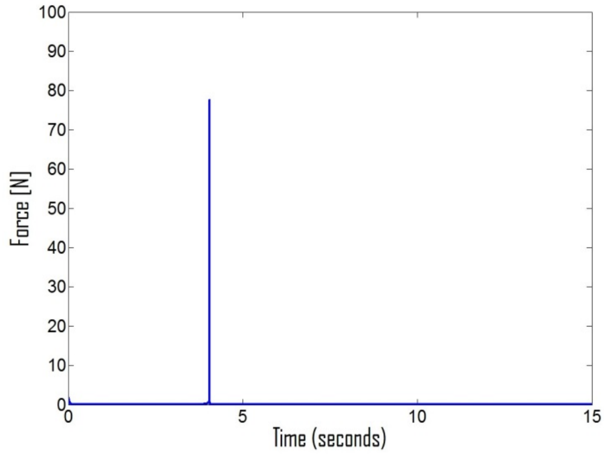

Fig. 8 f_m by PIC with Estimate inertial = 1.8 × real inertial parameter.

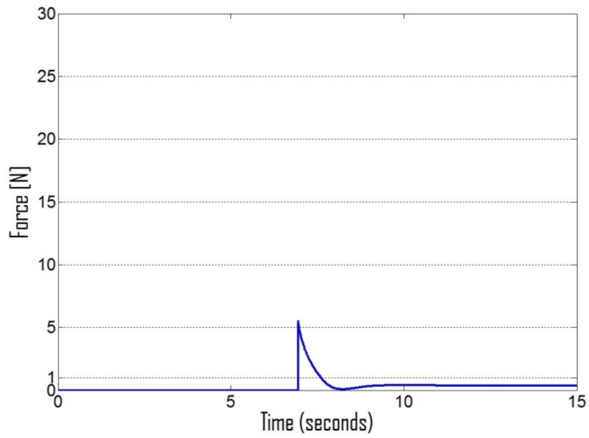

Fig. 9 The contact force by RPIC with Estimate inertial = 1.8×real inertial parameter.

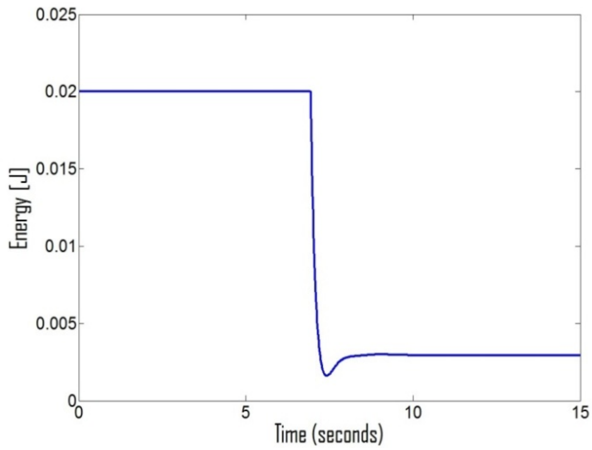

Fig. 10 The mechanic energy by RPIC with Estimate inertial = 1.8 × real inertial parameter.

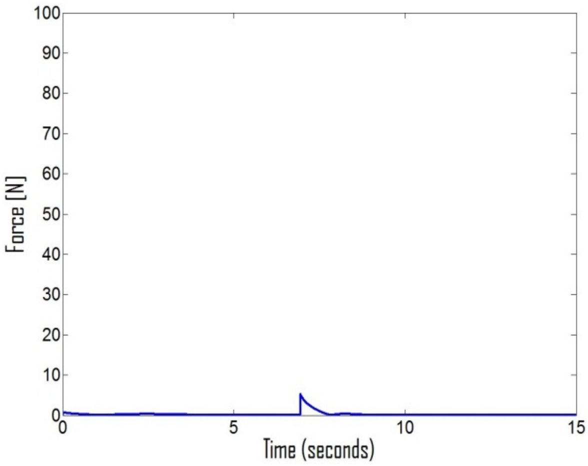

Fig. 11 f_m by RPIC with Estimate inertial = 1.8 × real inertial parameter.

Figs. 9 to 11 show the result using our robust passive impedance control. It is clear that, even if there are model errors, the contact forces converge to the value below 1 N after the robot punched the stiff wall and the mechanic energy of the robot has been limited below the initial value of 0.02 J.

By comparing this result with Figs. 6 to 8, it shows that the robot keeps passivity.

On the other hand, by comparing f_m under PIC with model errors and RPIC (Figs. 8 and 11), it is clear that RPIC method actually reduced the error force term f_m when end-effector of robot punches the stiff wall.

6. Conclusions

This paper studied how to keep the robot's passivity when the robot with model uncertainties interacts with its environment. We proposed robust passive impedance control approach. This approach adjusts the estimations of the robot's dynamic parameters in a simple way.

In order to verify the effectiveness of our approach, we performed a set of computer simulations. From these simulations, it is apparent that no matter how we change the robot's estimated physical parameters, our approach can keep the robot's passivity such that it greatly reduced the contact force from the environment.

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