Control of a Flexible Manipulator with Noncollocated Feedback: Time Domain Passivity Approach

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1. Introduction

Flexible manipulators are finding their way in industrial and space robotics applications due to their lighter weight and faster response time compared to rigid manipulators. Control of flexible manipulators has been studied extensively for more than a decade by several researchers (Book 1993, Cannon and Schmitz 1984, De Luca and Siciliano 1989, Siciliano and Book 1988, Vidyasagar and Anderson 1989, and Wang and etc. 1989). Despite their applications, control of flexible manipulators has proven to be rather complicated.
It is well known that stabilization of a flexible manipulator can be greatly simplified by collocating the sensors and the actuator, in which the input-output mapping is passive (Wang and Vidyasagar 1990), and a stable controller can be easily devised independent of the structure details. However, the performance of this collocated feedback turns out to be not satisfactory due to a week control of the vibrations of the link (Chudavarapu and Spong 1996). This initiated finding other noncollocated output measurements like the position of the end-point of the link to increase the control performance (Cannon and Schmitz 1984). However, if the end-point is chosen as the output and the joint torque is chosen as the input, the system becomes a nonminimum phase one, hence possibly behave actively. As a result, the small increment of the output feedback controller gains can easily make the closed-loop system unstable. This had led many researchers to seek other outputs for which the passivity property is enjoyed.
Wang and Vidyasagar (1990) proposed the so-called reflected tip position as such an output. This corresponds to the rigid body deflection minus the deflection at the tip of the flexible manipulator. Pota and Vidyasagar (1991) used the same output to show that in the limit, for a non uniform link, the transfer function from the input torque to the derivative of the reflected tip position is passive whenever the ratio of the link inertia to the hub inertia is sufficiently small. Chodavarapu and Spong (1996) considered the virtual angle of rotation, which consists of the hub angle of rotation augmented with a weighted value of the slope of the link at its tip. They showed that the transfer function with this output is minimum phase and that the zero dynamics are stable.

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Despite the fact that these previous efforts have succeeded in numerous kinds of applications, the critical drawback was that these are model-based approaches requiring the system parameters or the dynamic structure information at the least. However, interesting systems are uncertain and it is usually hard to obtain the exact dynamic parameters and structure information.

In this paper, we introduce a different way of treating noncollocated control systems without any model information. Recently developed stability guaranteed control method based on time-domain passivity control (Hannaford and Ryu 2002, Ryu, Kwon, and Hannaford 2002) is applied.

2. Review of stability guaranteed control with time domain passivity approach

2.1 Network model

In our previous paper (Ryu, Kwon, and Hannaford 2002), the traditional control system view could be analyzed in terms of energy flow by representing it in a network point of view. Energy here was defined as the integral of the inner product between the conjugate input and output, which may or may not correspond to a physical energy. We partition the traditional control system into three elements, the trajectory generator (consisting of the trajectory generator), the control element (consisting of the controller, actuator and sensors) and the plant (consisting of the plant). The connection between the controller element and the plant is a physical interface at which, suitable conjugate variables define the physical energy flow between controller and plant. The connection between trajectory generator and controller, which traditionally consists of a one-way command information flow, is modified by the addition of a virtual feedback of the conjugate variable. For a motion control system, the trajectory generator output would be a desired velocity (v_d), and the virtual feedback would be equal to the controller output (τ) (Fig. 1).

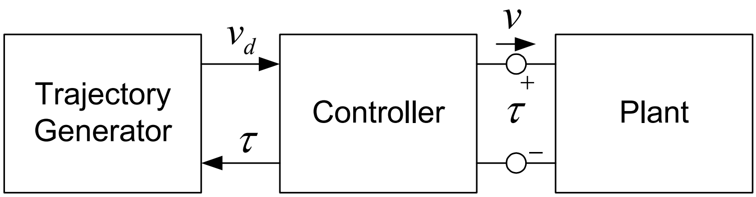

Fig. 1. Network view of a motion control system

To show that this consideration is generally possible for motion control systems, we physically interpret these energy flows. We consider a general tracking control system with a position PID and feed forward controller for moving a mass (M) on the floor with a desired velocity (v_d). The control system can be described by a physical analogy with Fig. 2. The position PD controller is physically equivalent to a virtual spring and damper whose reference position is moving with a desired velocity (v_d). In addition Integral Controller (u_I) and the feed forward controller (u_{FF}) can be regarded as internal force sources. Since the mass and the reference position are connected with the virtual spring and damper, we can obtain the desired motion of the mass by moving the reference position with the desired velocity. The important point is that if we want to move the reference position with the desired velocity (v_d), force is required. This force is determined by the impedance of the controller and the plant. Physically this force is equivalent to the controller (PID and feed forward) output (τ). As a result, the conjugate pair $(v_d \text{ and } \tau)$ simulates the flow of virtual input energy from the trajectory generator, and the conjugate pair $(v \text{ and } \tau)$ simulates the flow of real output energy to the plant. Through the above physical interpretation, we can construct a network model for general tracking control systems (Fig. 1), and this network model is equivalently described with Fig. 3 whose trajectory generator is a current (or velocity) source with electrical-mechanical analogy. Note that electrical-mechanical analog networks enforce equivalent relationships between effort and flow. For the mechanical systems, forces replace voltages in representing effort, while velocities representing currents in representing flow.

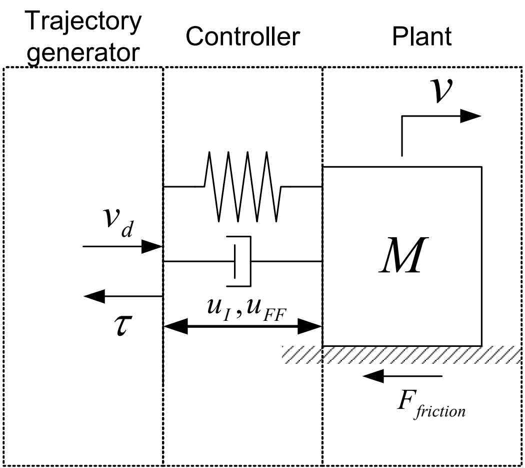

Fig. 2. Physical analogy of a motion control system

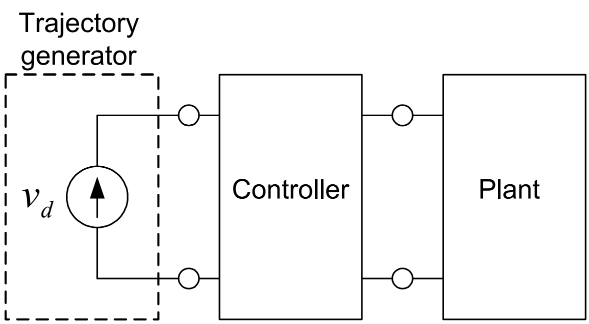

Fig. 3. Network view of general motion control systems

2.2 Stability concept

From the circuit representation (Fig. 4), we find that the virtual input energy from the trajectory generator depends on the impedance of the connected network. If the connected network (controller and plant) with the trajectory generator is passive, the control system can remain passive (Desoer and Vidyasagar 1975) since the trajectory generator creates just the amount of energy necessary to make up for the energy losses of the connected passive network. This is just like a normal electric circuit. Thus we have to make the connected network passive to guarantee the stability of the control system since passivity is a sufficient condition for stability.
In addition, the plant is uncertain and has a wide variation range of impedance or admittance (from zero to infinite). Thus, the controller 2-port should be passive to guarantee stability with any passive plant.

2.3 Time domain passivity approach

A new, energy-based method has been presented for making large classes of control systems passive by making the controller 2-port passive based on the time-domain passivity concept. In this section, we briefly review time-domain passivity control.
First, we define the sign convention for all forces and velocities so that their product is positive when power enters the system port (Fig. 4). Also, the system is assumed to have initial stored energy at t = 0 of E(0). The following widely known definition of passivity is used.

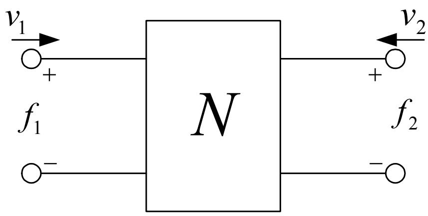

Fig. 4. Two-port network

Definition 1: *The two-port network, N, with initial energy storage $E(0)$ is passive if and only if,*

$$\int_0^t \left(f_1(\tau)v_1(\tau) + f_2(\tau)v_2(\tau)\right)d\tau + E(0) \geq 0, \qquad \forall t \geq 0 \tag{1}$$

for admissible forces (f_1, f_2) and velocities (v_1, v_2).
Equation (1) states that the energy supplied to a passive network must be greater than negative E(0) for all time (van der Schaft 2000, Adams and Hannaford 1999, Desoer and Vidyasagar 1975, Willems 1972).
The conjugate variables that define power flow in such a computer system are discrete-time values, and the analysis is confined to systems having a sampling rate substantially faster than the dynamics of the system so that the change in force and velocity with each sample is small. Thus, we can easily "instrument" one or more blocks in the system with the following "Passivity Observer," (PO) for a two-port network to check the passivity (1).

$$E_{obsv}(n) = \Delta T \sum_{k=0}^{n} \left(f_1(k)v_1(k) + f_2(k)v_2(k)\right) + E(0) \tag{2}$$

where ΔT is the sampling period.
If $E_{obsv}(n) \geq 0$ for every n, this means the system dissipates energy. If there is an instance when $E_{obsv}(n) < 0$, this means the system generates energy and the amount of generated energy is $-E_{obsv}(n)$.
Consider a two-port system which may be active. Depending on operating conditions and the specifics of the two-port element's dynamics, the PO may or may not be negative at a particular time. However, if it is negative at any time, we know that the two-port may then be contributing to instability. Moreover, we know the exact amount of energy generated and we can design a time-varying element to dissipate only the required amount of energy. We call this element a "Passivity Controller" (PC). The PC takes the form of a dissipative element in a series or parallel configuration for the input causality (Hannaford and Ryu 2002).

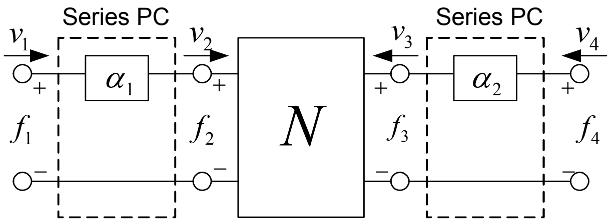

Fig. 5. Configuration of series PC for 2-port network

For a 2-port network with impedence causality at each port, we can design two series PCs (Fig. 5) in real time as follows:

1) $v_1(n) = v_2(n)$ and $v_3(n) = v_4(n)$ are inputs
2) $f_2(n)$ and $f_3(n)$ are the outputs of the system.
3) $W(n) = W(n-1) + f_2(n)v_2(n) + f_3(n)v_3(n) + \alpha_1(n-1)v_2(n-1)^2 + \alpha_2(n-1)v_3(n-1)^2$ is the PO

Two series PCs can be designed for several cases

4)
$$\alpha_1(n) = \begin{cases} -W(n)/v_2(n)^2 & \text{if case } 2, 4.2 \\ \dfrac{-f_2(n)v_2(n)}{v_2(n)^2} & \text{if case } 4.1 \\ 0 & \text{if case } 1, 3 \end{cases} \tag{3}$$

5)
$$\alpha_2(n) = \begin{cases} -W(n)/v_3(n)^2 & \text{if case } 3 \\ \dfrac{-(W(n-1) + f_3(n)v_3(n))}{v_3(n)^2} & \text{if case } 4.1 \\ 0 & \text{if case } 1, 2, 4.2 \end{cases} \tag{4}$$

where each case is as follows:
Case 1: energy does not flow out

$$W(n) \geq 0$$

Case 2: energy flows out from the left port

$$W(n) < 0,\ f_2(n)v_2(n) < 0,\ f_3(n)v_3(n) \geq 0$$

Case 3: energy flows out from the right port

$$W(n) < 0,\ f_2(n)v_2(n) \geq 0,\ f_3(n)v_3(n) < 0$$

Case 4: energy flows out from the both ports: as we mentioned above, in this paper, we divide it into two cases. The first case is when the produced energy from the right port is greater than the previously dissipated energy:

$$4.1\ \ W(n) < 0,\ f_2(n)v_2(n) < 0,\ f_3(n)v_3(n) < 0, W(n-1) + f_3(n)v_3(n) < 0$$

in this case, we only have to dissipate the net generation energy of the right port as the second line in Eq. (4). The second case is when the produced energy from the right port is less than the previously dissipated energy:

$$4.2\ \ W(n) < 0,\ f_2(n)v_2(n) < 0,\ f_3(n)v_3(n) < 0, W(n-1) + f_3(n)v_3(n) \geq 0$$

in this case we don't need to activate the right port PC, and also reduce the conservatism of the left port PC as the fist line of Eq. (3).

6) $f_1(n) = f_2(n) + \alpha_1(n)\, v_2(n) \Rightarrow$ output

7) $f_4(n) = f_3(n) + \alpha_2(n)\, v_3(n) \Rightarrow$ output

Please see (Ryu, Kwon and Hannaford 2002a, 2002b) for more detail about two-port time domain passivity control approach.

3. Implementation issues

This section addresses how to implement the time domain passivity control approach to flexible manipulator with noncollocated feedback. Consider a single link flexible manipulator having a planar motion, as detailed in Fig. 6. v_e is the end-point velocity, v_a is the velocity of the actuating position, and τ is the control torque at the joint.

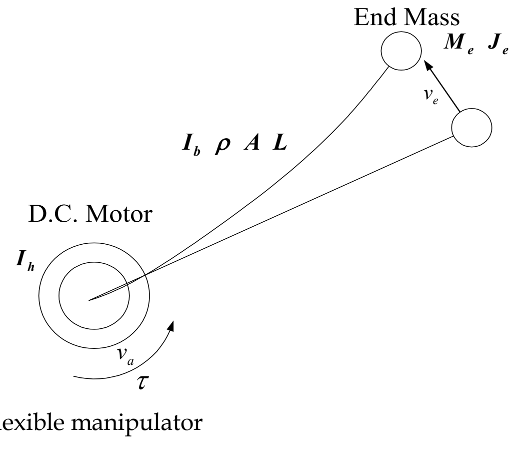

Fig. 6. A Single-link flexible manipulator

3.1 Network modeling

When we feedback end-point position to control the motion of the flexible manipulator, a network model (including causality) of the overall control system is depicted as in Fig. 7. v_{ed} means a desired velocity of the end-point. In this case, we have to consider one important thing. If the input-output relation of the plant is active, the time domain passivity control scheme cannot be applied, since the time domain passivity control scheme has been developed in the framework that the input-output relation of the plant is passive. If the end-point position is a plant output and joint torque is a plant input, the input-output relation of the plant is possibly active. Thus the overall control system may not be passive even though the controller remains passive.

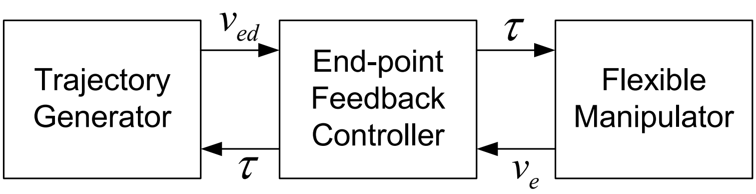

Fig. 7. A network model of flexible manipulator with end-point feedback

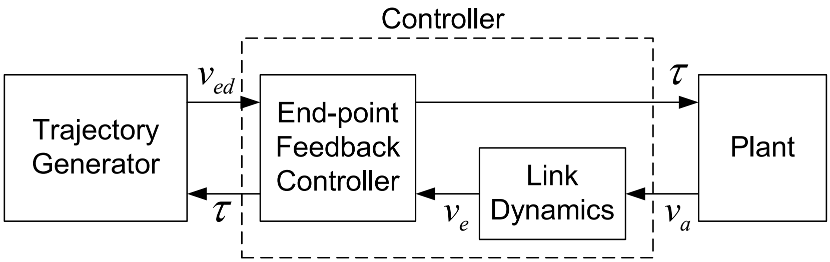

Fig. 8. A network model of flexible manipulator with end-point feedback

To solve this problem, we make the above network model suitable to our framework. The important physical fact is that the conjugate input-output pair (v_e, τ) is not simulating physical output energy from the controller to the flexible manipulator, the energy flows into the flexible manipulator through only the place where the actuator is attached. Even the controller use non-collocated sensor information to generate controller output, the actual physical energy that is transmitted to the flexible manipulator is determined by the conjugate pair at the actuating position. Based on the above inspection, it is clear that the controlled result about the joint torque is joint velocity, and the joint velocity cause end-point motion. Therefore, we can extract a link dynamics from the joint velocity to the end-point velocity from the flexible manipulator (which has noncollocated feedback) as in Fig. 8. The noncollocated (possibly active) system is then separated into the collocated (passive) system and a dynamics from the collocated output (joint velocity) to the noncollocated output (end-point velocity). As a result, if it is possible, and it generally is, to use the velocity information of the actuating position, we can construct the network model (controller and passive plant) that is suitable to our framework as in Fig. 8 by including the link dynamics that cause the noncollocation problem into the controller.

3.2 Designing the PO/PC

First, for designing the PO, it is necessary to check the real-time availability of the conjugate signal pairs at each port of the controller. The conjugate pair at the port that is connected with the trajectory generator is usually available since the desired trajectory (v_{ed}) is given and the controller output (τ) is calculated in real-time. Furthermore, the conjugate pair is generally available for the other port that is connected to the plant since the same controller output (τ) is used, and the output velocity of the actuating position (v_a) is measured in real-time. Thus, the PO is designed as

$$E_{obsv}(n) = \Delta T \sum_{k=0}^{n} \left(\tau(k) v_{ed}(k) - \tau(k) v_a(k)\right) + E(0) = \Delta T \cdot W(n).$$

After designing the PO, the causality of each port of the controller should be determined in order to choose the type of PC for implementation. In a noncollocated flexible manipulator control system, the output of the trajectory generator is the desired velocity (v_{ed}) of the end-point, and the controller output (τ) is feedback to the trajectory generator. Thus, the port that is connected with the trajectory generator has impedance causality. Also, the other port of the controller has impedance causality because a motion controlled flexible manipulator usually has admittance causality (force input (τ) and joint velocity output (v_a)). Thus, two series PCs have to be placed at each port to guarantee the passivity of the controller (Fig. 9). From the result in (Ryu, Kwon and Hannaford 2002b), the initial energy of the controller is as follows:

$$E(0) = \frac{1}{2} K_p e(0)^2$$

where K_p is a proportional gain and $e(0)$ is the position error of the end-point at the starting time.

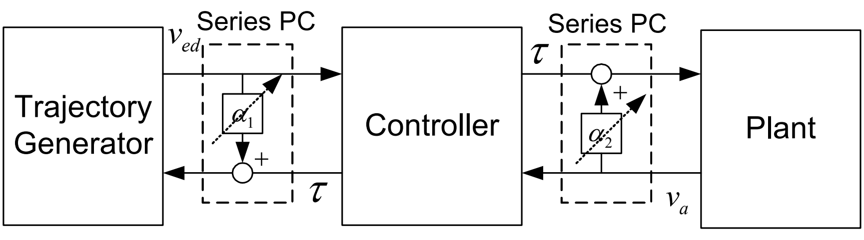

Fig. 9. Configuration of PC for a flexible manipulator with end-point feedback

4. Simulation examples

Many researchers have used a flexible manipulator for testing newly developed control methods due to its significant control challenges. In this section, the proposed stability guaranteed control scheme for noncollocated control systems is tested for feasibility with a simulated flexible link manipulator.

The experimentally verified single link flexible manipulator model (Kwon and Book 1994) is employed in this paper. A single link flexible manipulator having a planar motion is detailed in Fig. 6. The rotational inertia of the servo motor, the tachometer, and the clamping hub are modeled as a single hub inertia I_h. The payload is modeled as an end mass M_e and a rotational inertia J_e. The joint friction is included in the damping matrix. The system parameters in Fig. 6 are given in Table 1. The closed form dynamic equation is derived using the assumed mode method. For the system dynamic model, the flexible mode is modeled up to the third mode, that is, an 8th order system is considered.

In this section, a stable tip position feedback control is achieved for a flexible manipulator by using the PO/PC.

The following PD controller gain is used

$$K_P = 30\,,\ \ K_D = 0.8$$

In this noncollocated feedback systems, the hub angle can be considered as a conjugate pair with joint torque to calculate physical energy output flow into the flexible manipulator (see Section 3.A).

Without the PC turned on, tip-position tracking control is simulated (Fig. 10). The desired tip-position trajectory is as follows:

$$x_d(t) = 0.1\sin(t)$$

Link	EI : stiffness (Nm^2)	11.85	H : thickness (m)	47.63E-4
	ρ A : unit length mass (kg/m)	0.2457	L : length	1.1938
Tip mass	M_e : mass (kg)	0.5867	Je : rot. Inertia (kgm^2)	0.2787
Hub	I_h : rot. Inertia (kgm^2)		0.016	

Table 1. Physical properties of a single-link flexible manipulator

The tip-position can not follow the desired trajectory, tip position and control input have oscillation which increases with time (Fig. 10a,b), the PO (Fig. 10c) grow to more and more negative values.

Stable tip-position tracking is achieved with the PC turned on. Tip-position tracks the desired trajectory very well (Fig. 11a), and the PO is constrained to positive values (Fig. 11c). The PC at the both side is active only when these are required, and dissipate the just amount of energy generation (Fig. 11d)

5. Conclusions

In this paper, we propose a stability guaranteed control scheme of noncollocated feedback control systems without any model information. The main contribution of this research is proposing a method to implement the PO/PC for a possibility active plant due to the noncollocated feedback. We separate the active plant into passive one and a transfer function from the collocated output to the noncollocated output. Therefore, the control system can be fit to our PO/PC framework. As a result, we can achieve stable control even for the noncollocated control system.

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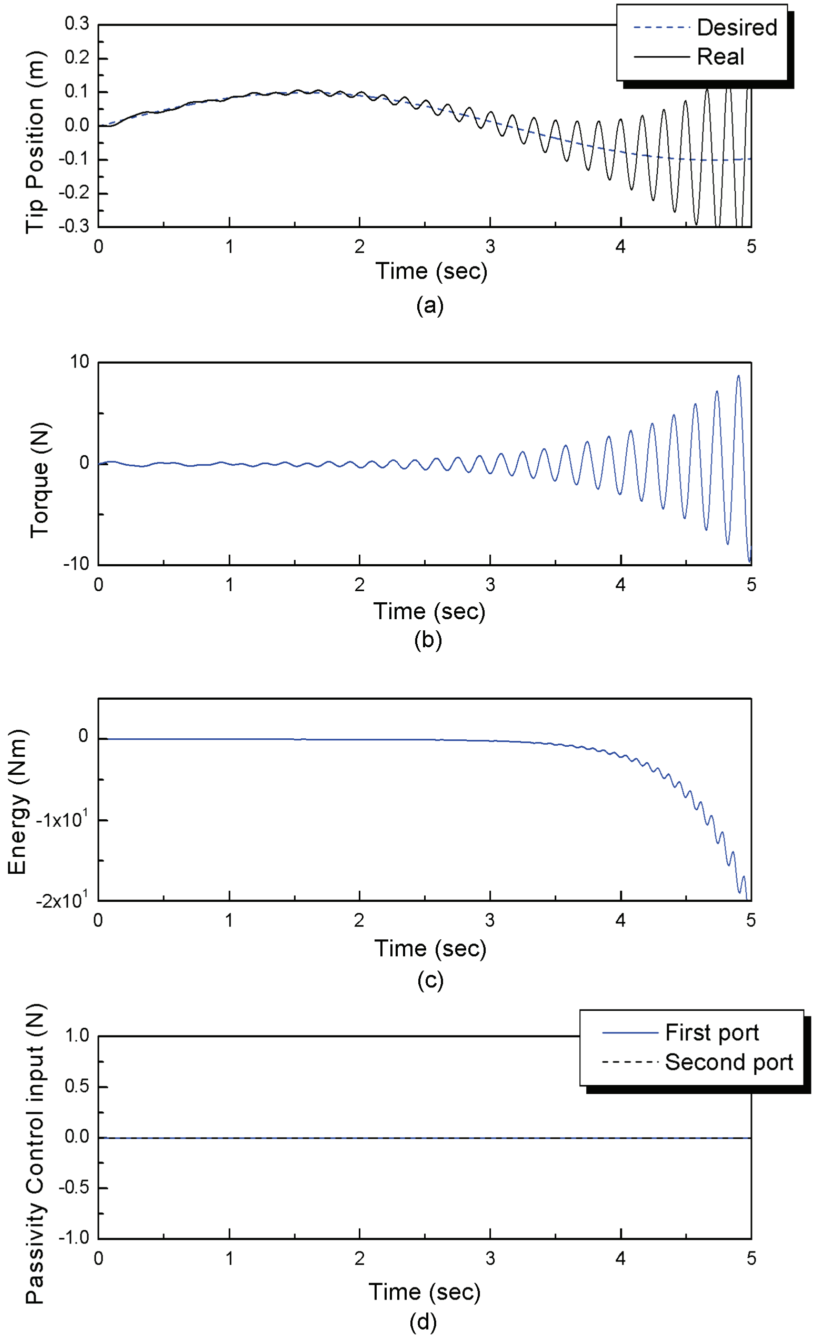


Fig. 10. Tip-position feedback without the PC

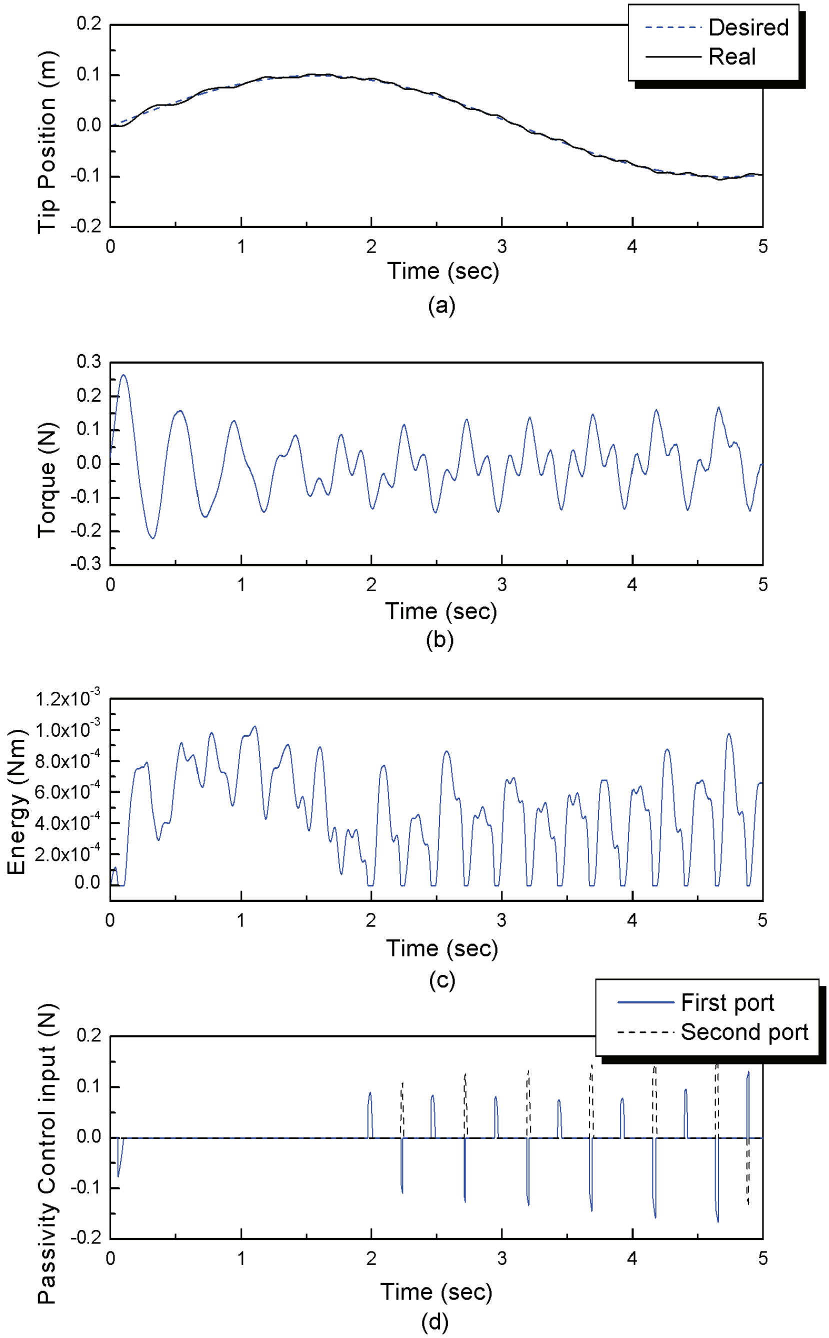
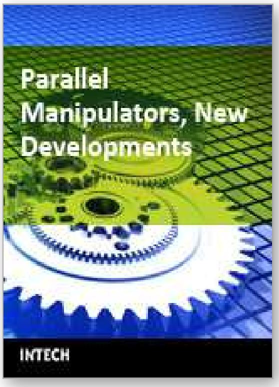


Fig. 11. Tip-position feedback with the PC



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Parallel manipulators are characterized as having closed-loop kinematic chains. Compared to serial manipulators, which have open-ended structure, parallel manipulators have many advantages in terms of accuracy, rigidity and ability to manipulate heavy loads. Therefore, they have been getting many attentions in astronomy to flight simulators and especially in machine-tool industries.The aim of this book is to provide an overview of the state-of-art, to present new ideas, original results and practical experiences in parallel manipulators. This book mainly introduces advanced kinematic and dynamic analysis methods and cutting edge control technologies for parallel manipulators. Even though this book only contains several samples of research activities on parallel manipulators, I believe this book can give an idea to the reader about what has been done in the field recently, and what kind of open problems are in this area.