# Time Domain Passivity Control of Haptic Interfaces with Virtual Environments

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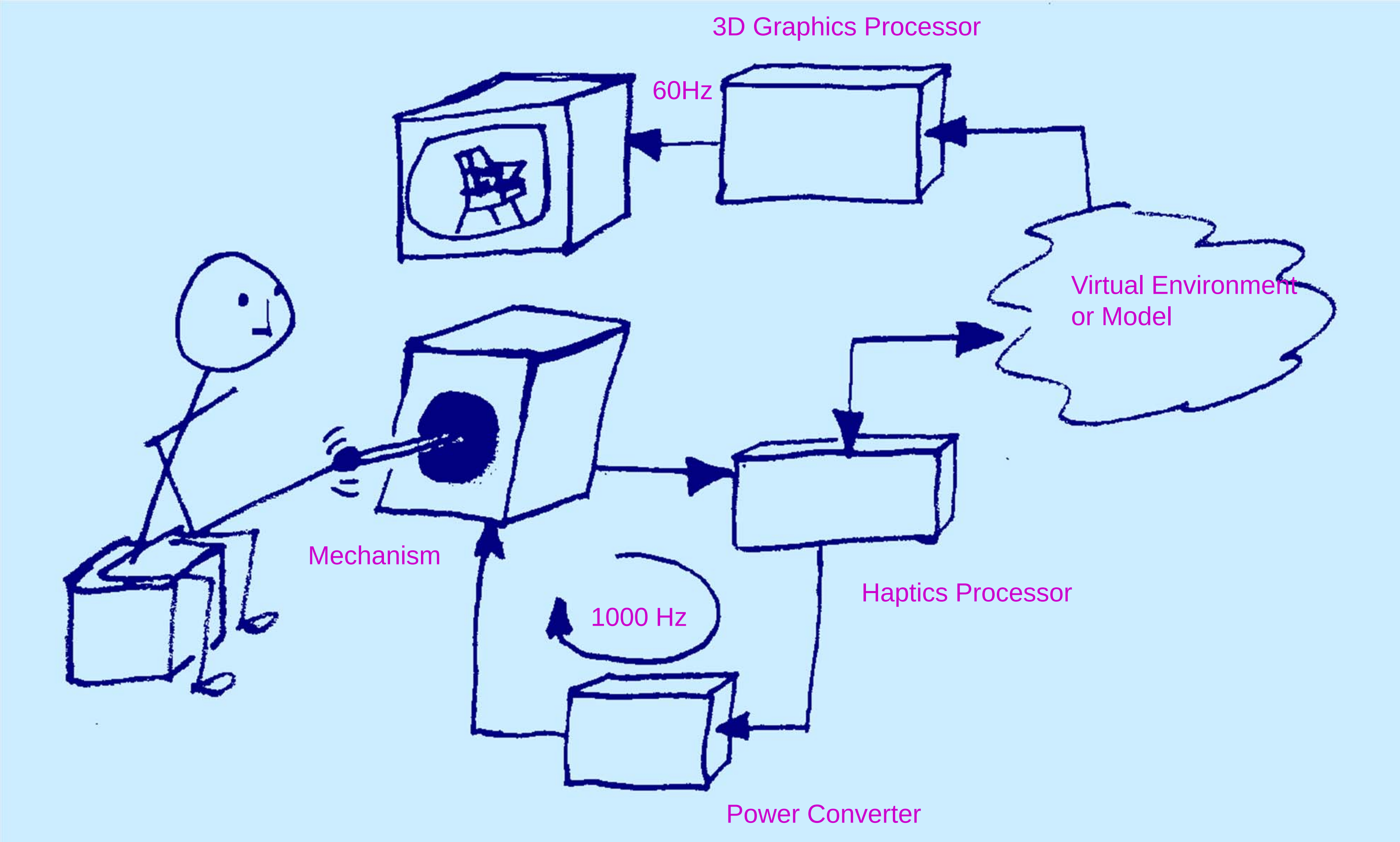
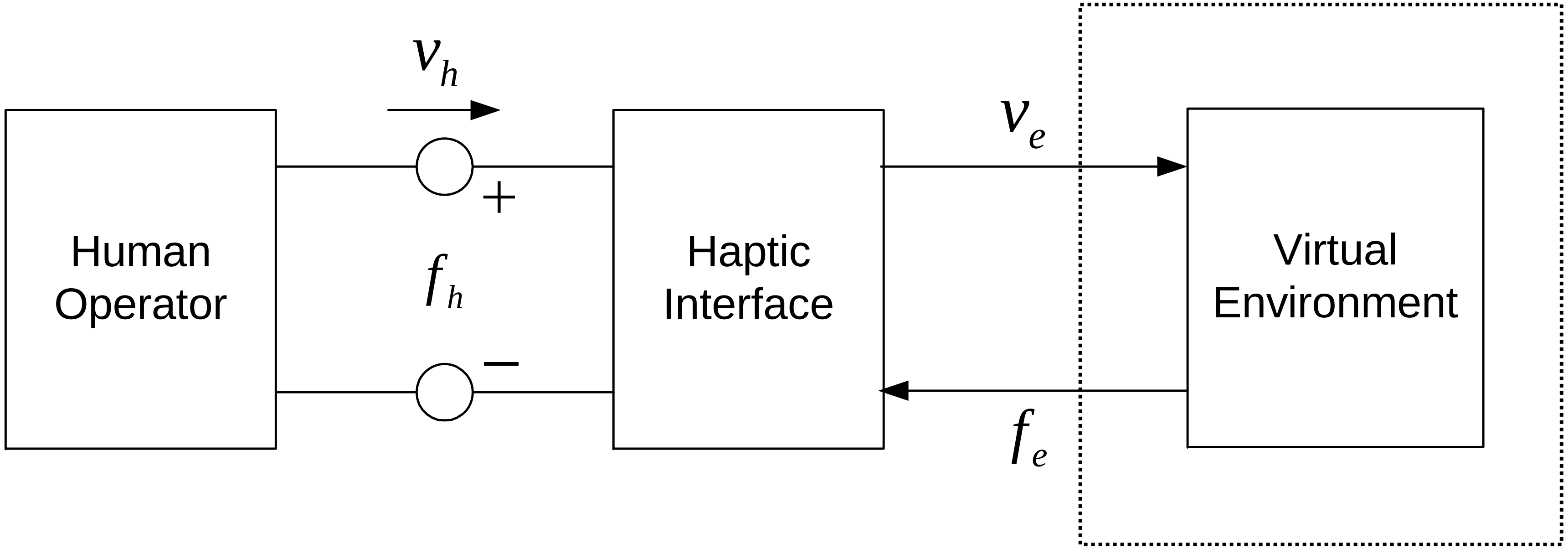
1. Stability Condition
2. Time Domain Passivity Approach
3. Experimental Results

# Haptic Interaction System Overview



# Network Model and Stability Condition



Virtual Environment one-port should be passive

$$\int_0^t f_e(\tau) v_e(\tau) d\tau \geq 0, \qquad \forall t \geq 0$$

# Passivity

- Principle of conservation of energy:
  - *"Energy supplied BY the network can never exceed the energy which has been fed TO it"*
- Mathematical definitions

$$\int_0^t f(\tau)v(\tau)d\tau + E(0) \ge 0, \qquad \forall t \ge 0$$

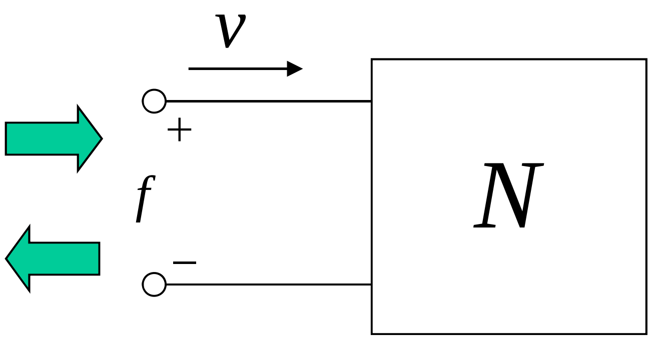
**Net energy supplied** **Initial energy storage**

$f$ : Force

$v$ : Velocity

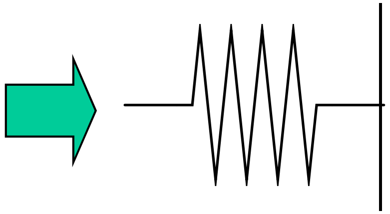
$f \cdot v > 0$

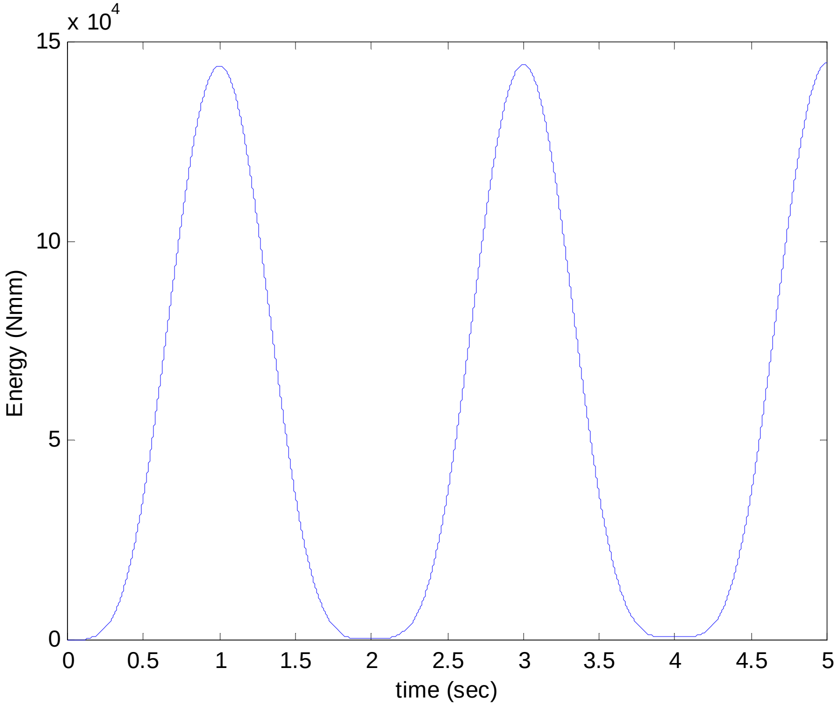
$f \cdot v < 0$



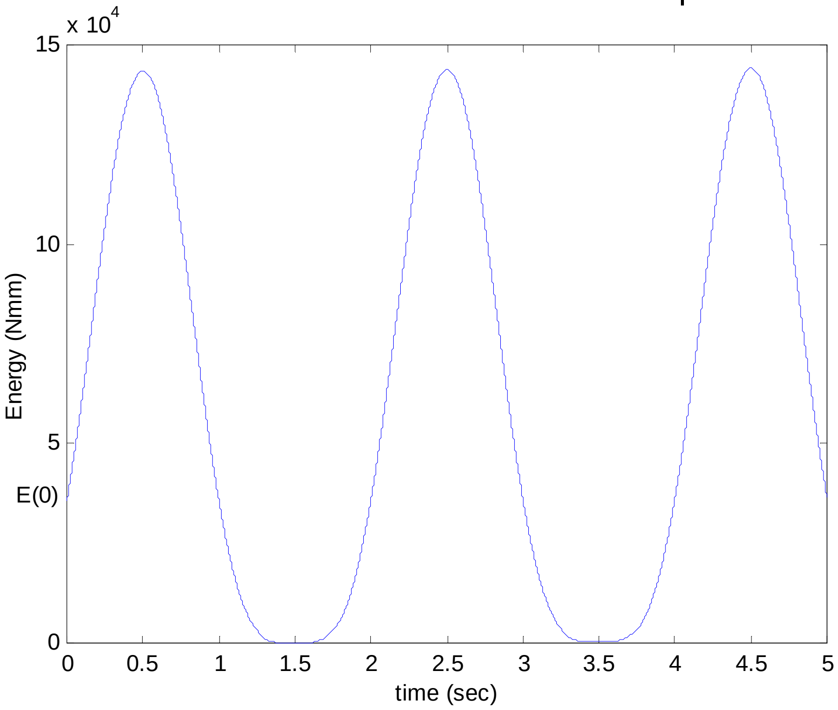
# Energy Behavior of Spring

$$\int_0^t f(\tau)v(\tau)d\tau + E(0) \geq 0, \qquad \forall t \geq 0$$





Zero initial condition



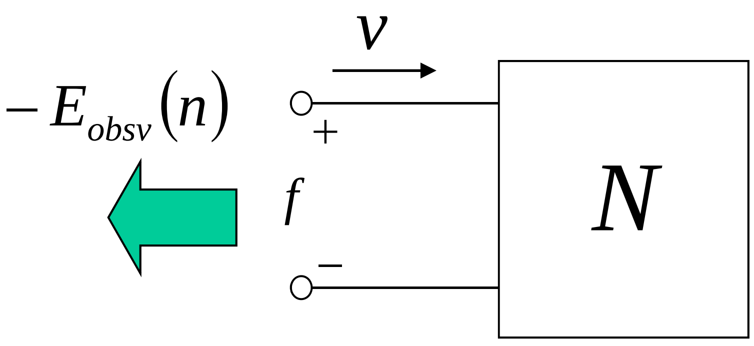
Initially deflected

# Passivity Observer (PO) can measure energy flow in real-time

Passivity :

$$\int_0^t f(\tau)v(\tau)d\tau \geq 0, \qquad \forall t \geq 0$$

PO : $E_{obsv}(n) = \Delta T \sum_{k=0}^{n} f(k)v(k)$

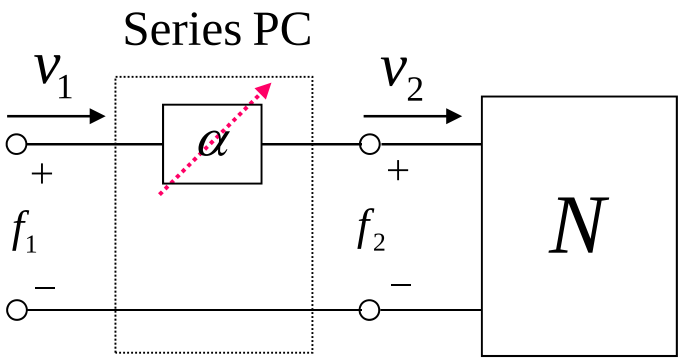


$E_{obsv}(n) \geq 0$ : Passive

$E_{obsv}(n) < 0$ : Active

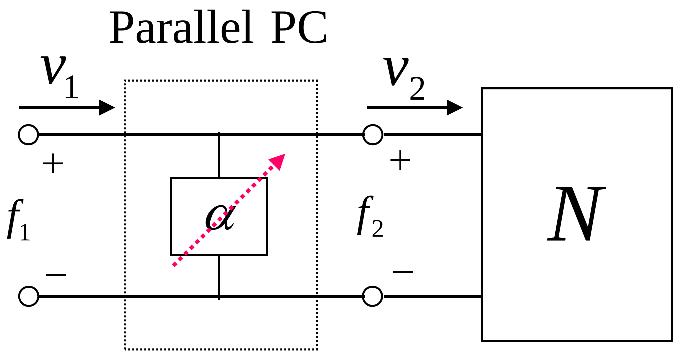
-Hannaford and Ryu 2001-

# Passivity Controller (PC) is an adaptive dissipation element



Series or velocity conserving

Impedance causality



parallel or force conserving

Admittance causality

-Hannaford and Ryu 2001-

# Series PC Algorithm

1) $v_1(n) = v_2(n)$ is an input

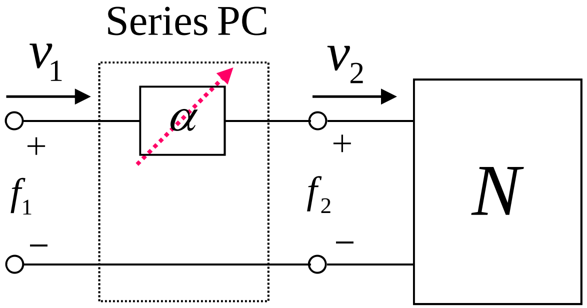
2) $f_2(n) = F_N(v_2(n))$

where $F_N(\ )$ is the output of the one-port

3) $E_{obsv}(n) = E_{obsv}(n-1) + [\, f_2(n) v_2(n) + \alpha(n-1) v_2(n-1)^2 \,]\Delta T$

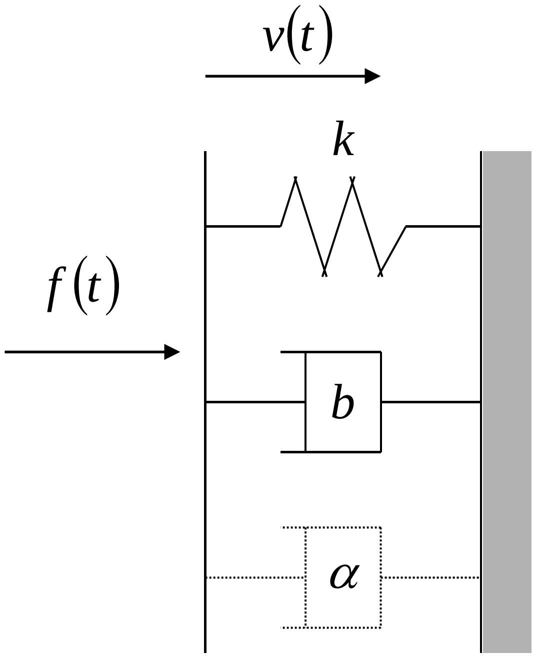
4) $\alpha(n) = \begin{cases} -E_{obsv}(n)/\Delta T\, v_2(n)^2 & \text{if } E_{obsv}(n) < 0 \\ 0 & E_{obsv}(n) \geq 0 \end{cases}$

5) $f_1(n) = f_2(n) + \alpha(n)\, v_2(n) \Rightarrow$ output



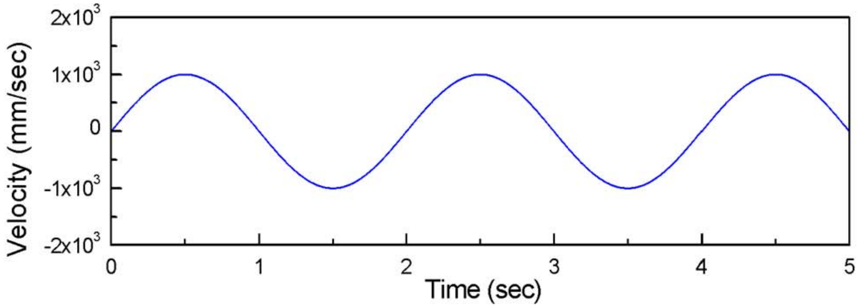
-Hannaford and Ryu 2001-

# Simple Simulation with Impedance Type Virtual Wall

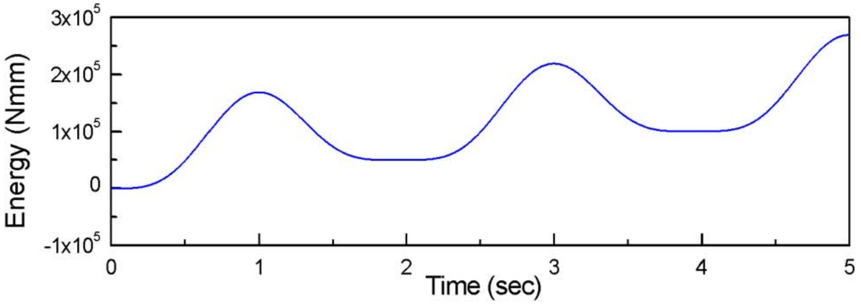


$k = 710\ N/m$
$b = 50\ Ns/m$

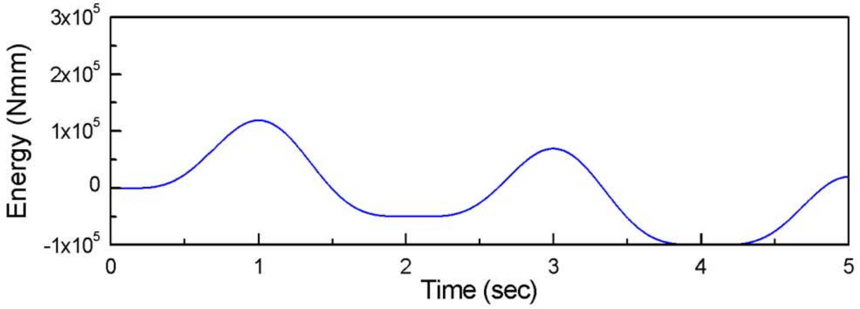
# Simulation Results



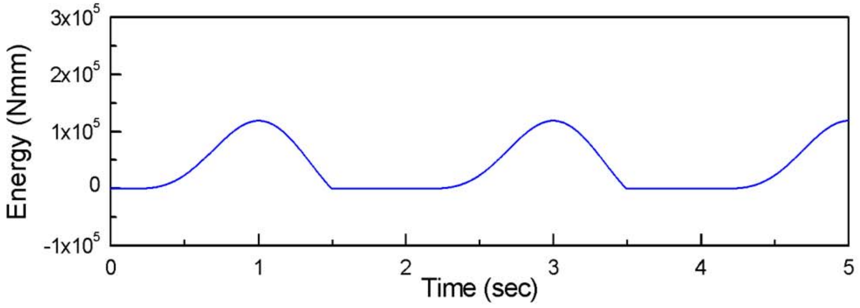
(a) Velocity Input



(b) Energy Dissipation

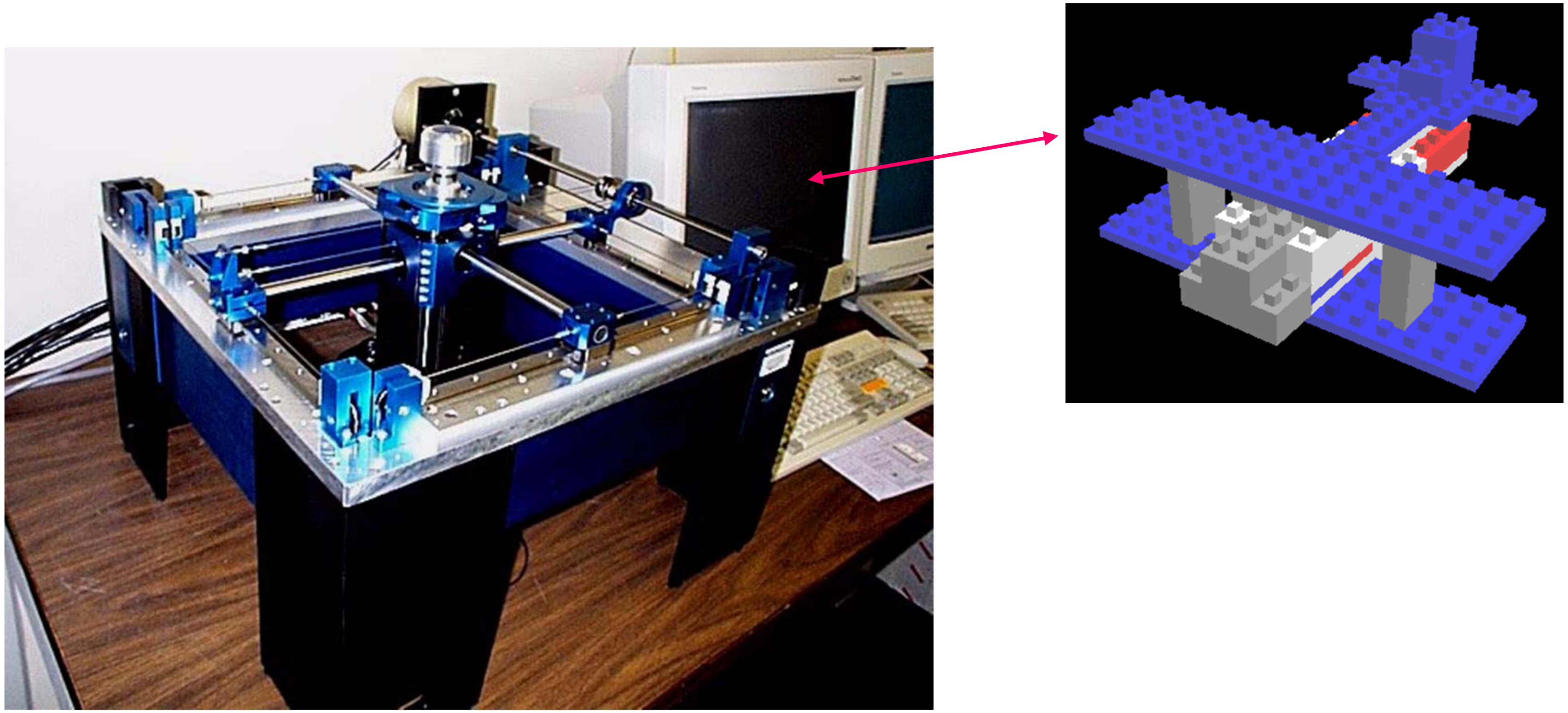


(c) Energy Generation



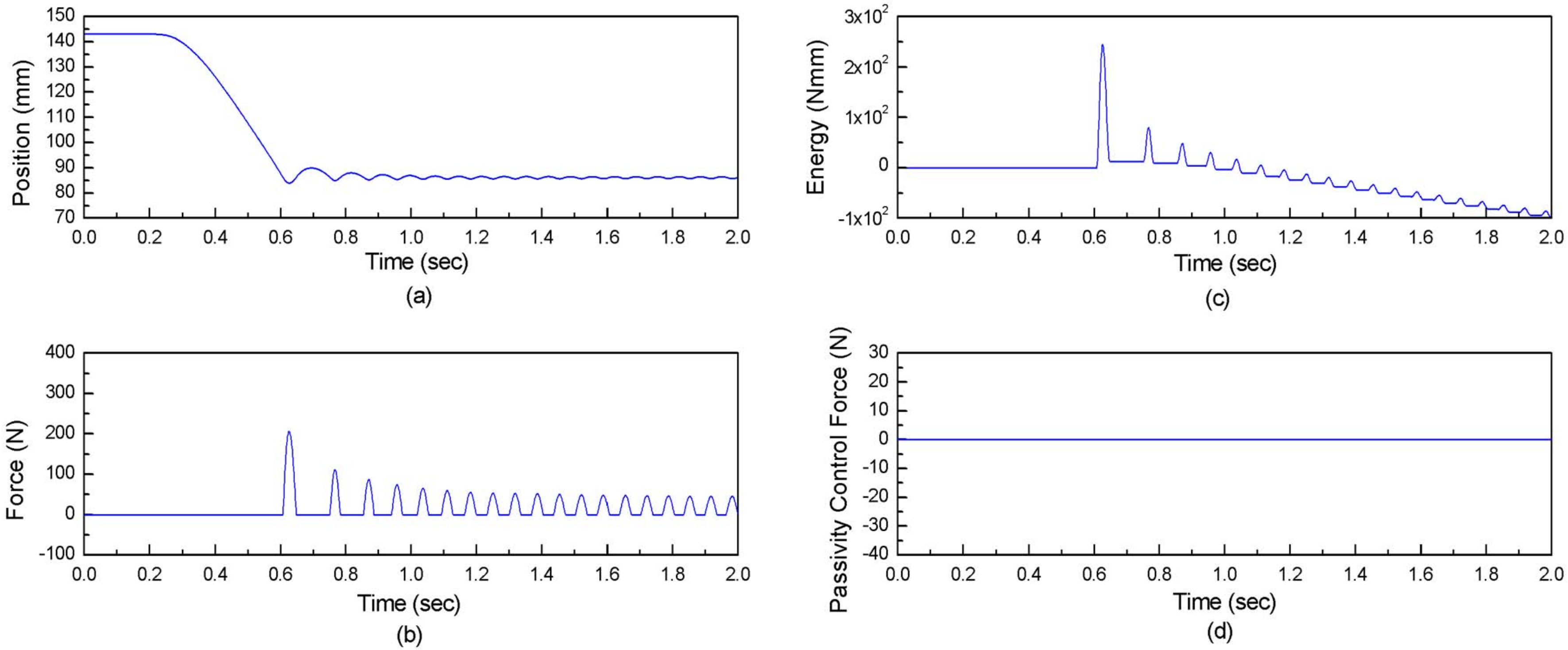
(d) Passivity Control

# Excalibur Haptic Interface System



# Experimental Video Clip

# Contact with High Stiffness without PC
# (*k* = 90 *kN/m*)



(a)

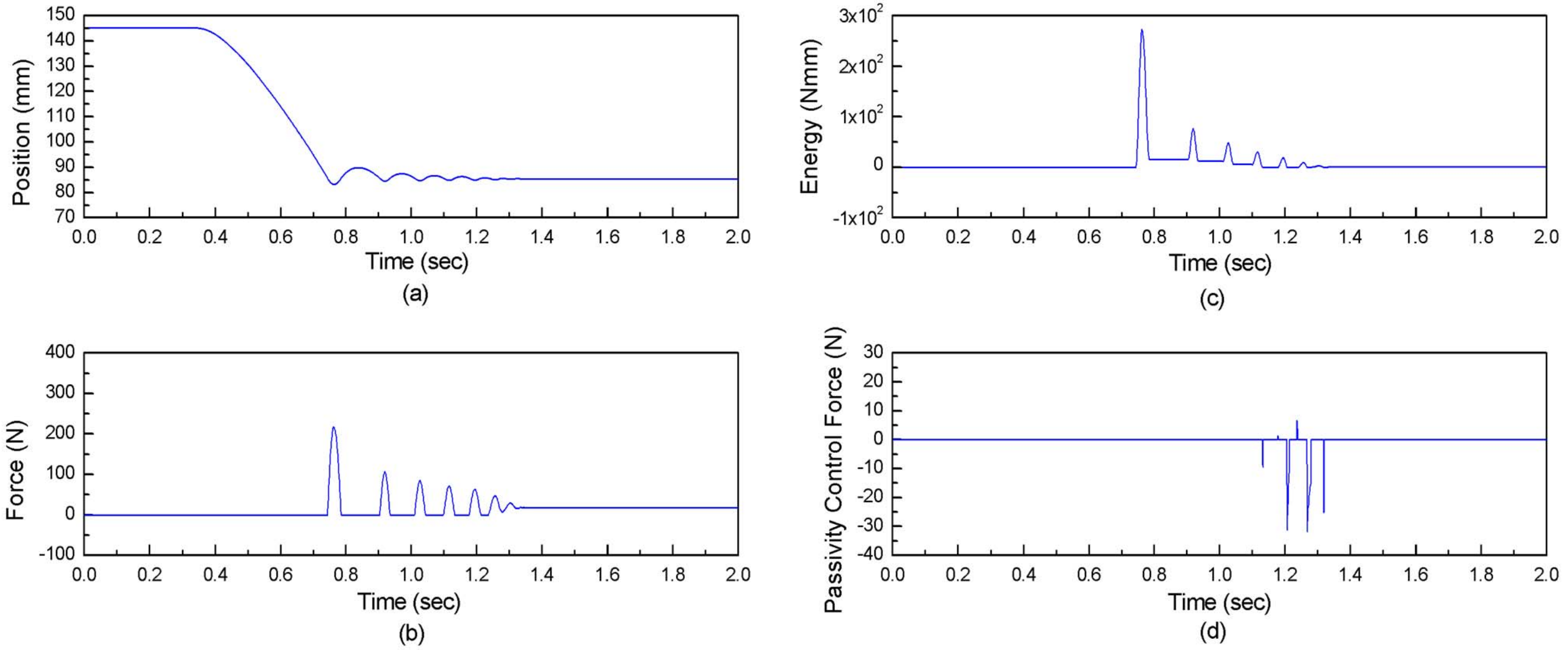
(c)

(b)

(d)

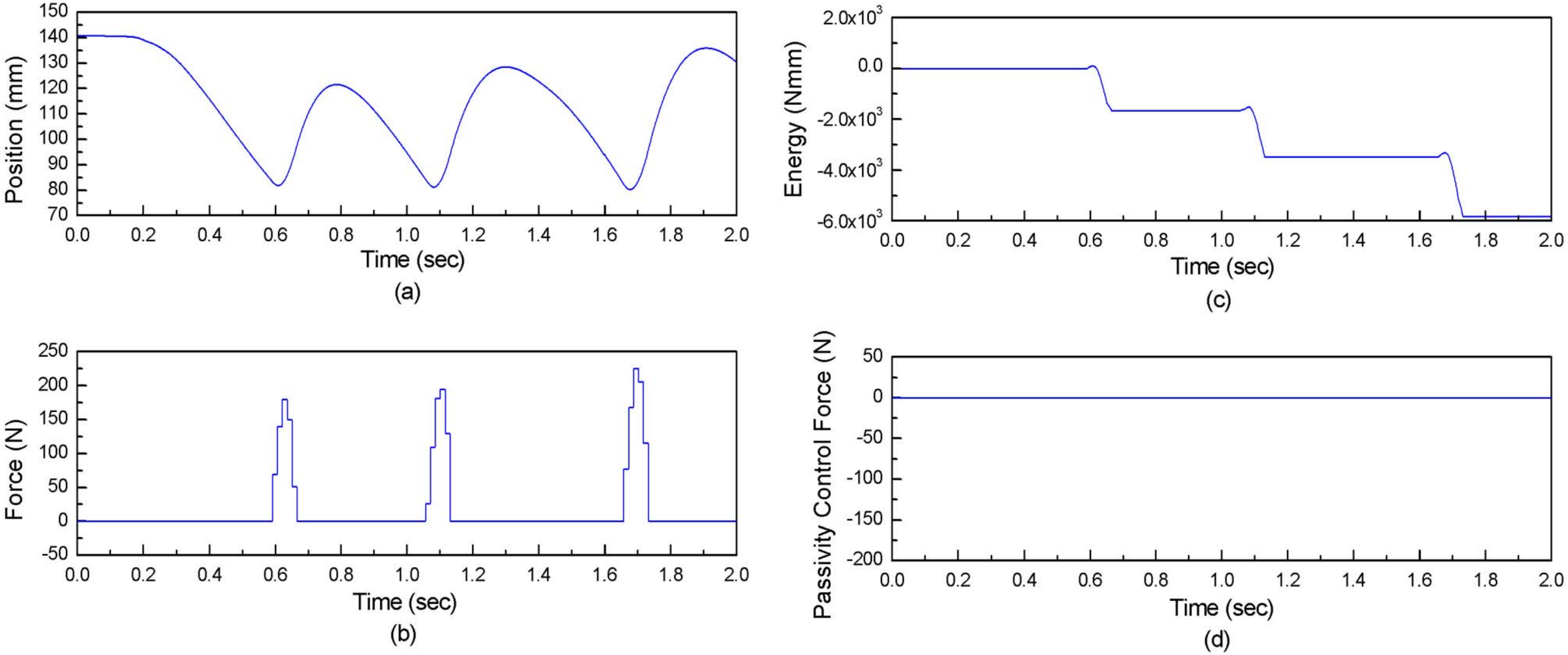
- ➢Contact was unstable
- ➢PO was initially positive, but grow to negative value

# Contact with High Stiffness with PC



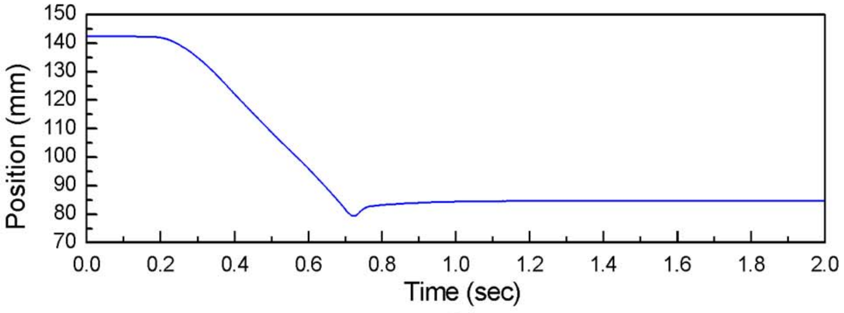
- ➢Stable contact was achieved with about 6 bounces
- ➢PC begin to operate on the 4th bounce

# Delayed environment without PC (66.67 *Hz*)

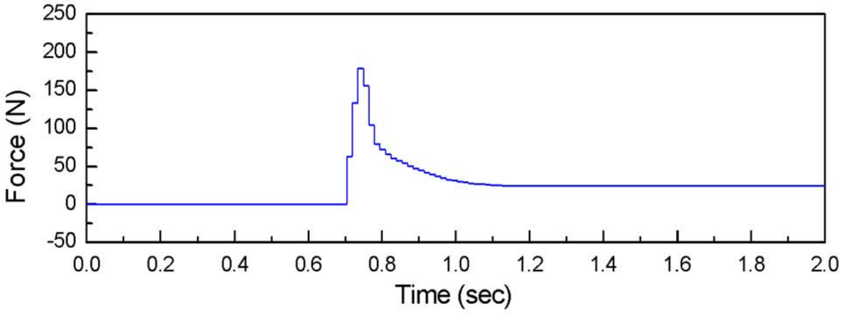


- One of the most challenging problem
- Result was very unstable

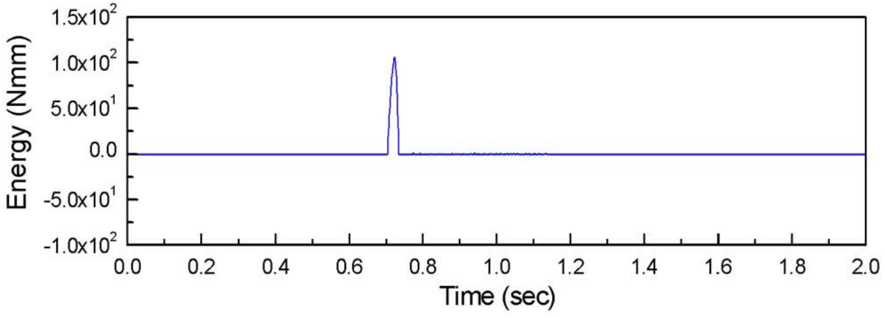
# Delayed environment with PC



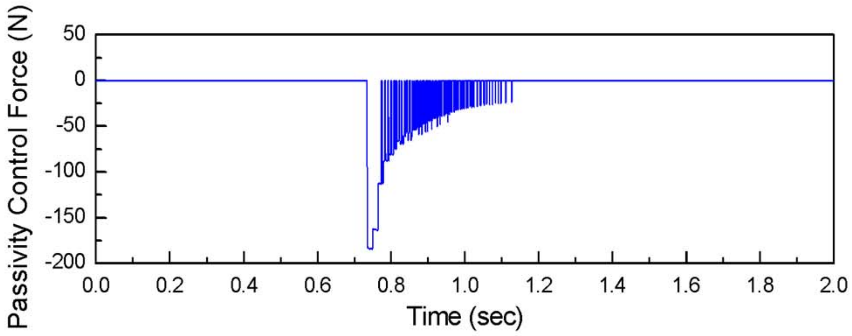
(a)



(b)



(c)



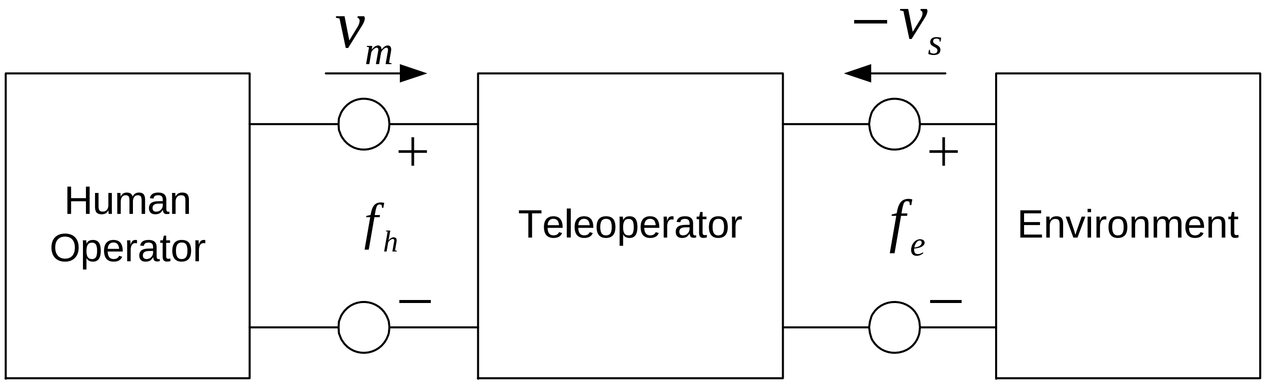
(d)

- ➢Contact is stabilized within a single bounce
- ➢Noisy behavior of PC coincide with a period of low velocity

# Stable Teleoperation with Time Domain Passivity Control

1. Stability Condition
2. Time Domain Passivity Approach
3. Experimental Results

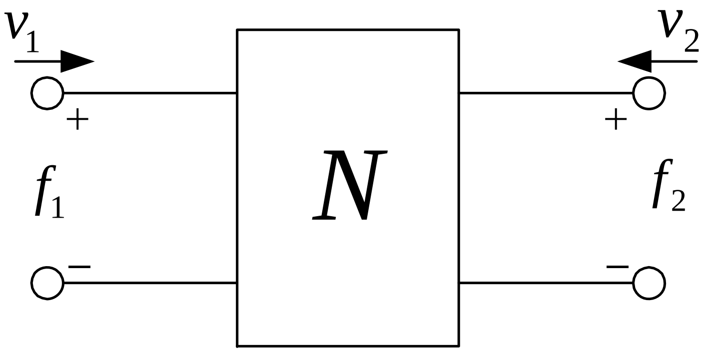
# Network Model and Stability Condition



Teleoperator two-port should be passive

$$\int_0^t \left( f_h(\tau) v_m(\tau) + f_e(\tau) v_s(\tau) \right) d\tau \geq 0, \qquad \forall t \geq 0$$

# Passivity Observer for 2-port network is similar

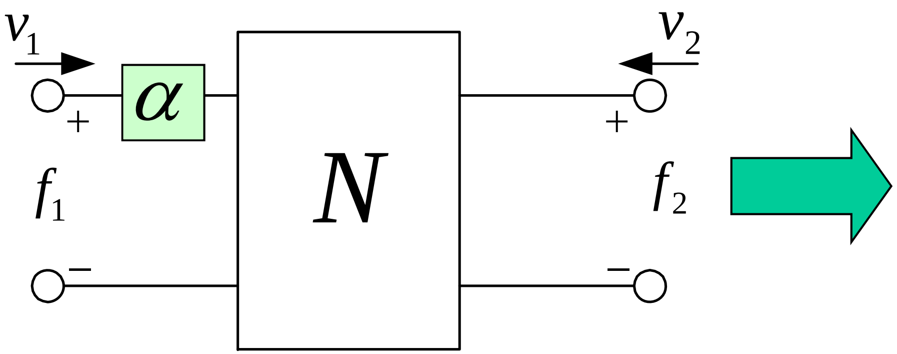


PO :

$$
\begin{aligned}
E_{obsv}(n) &= \Delta T \sum_{k=0}^{n} \left( f_1(k) v_1(k) + f_2(k) v_2(k) \right) + E(0) \\
&= \Delta T \cdot W(n)
\end{aligned}
$$

# Two PCs are required for 2-port network

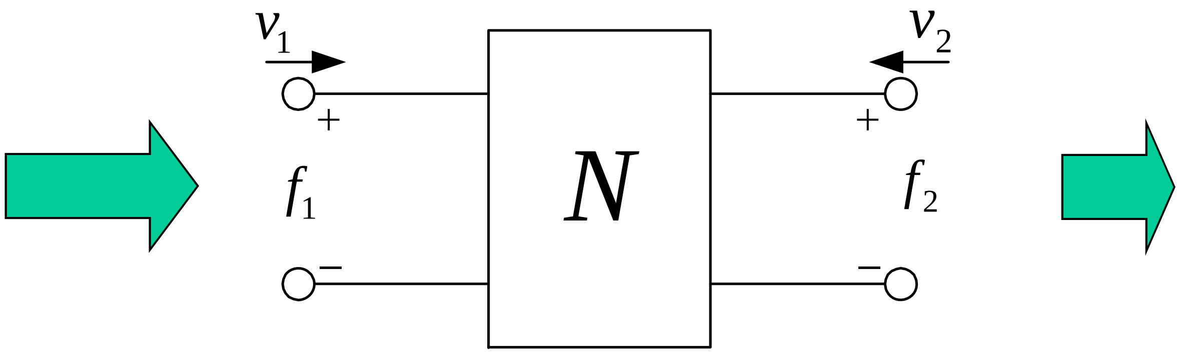
- There are two gate ways through which the generated energy flows out



$$v_1 = 0$$

# Mathematically there are two ways to make the 2-port network passive

- Increasing the absorbed energy
- Decreasing the produced energy



Add PC at each port and decrease the produced energy

# There are four cases of PC operation

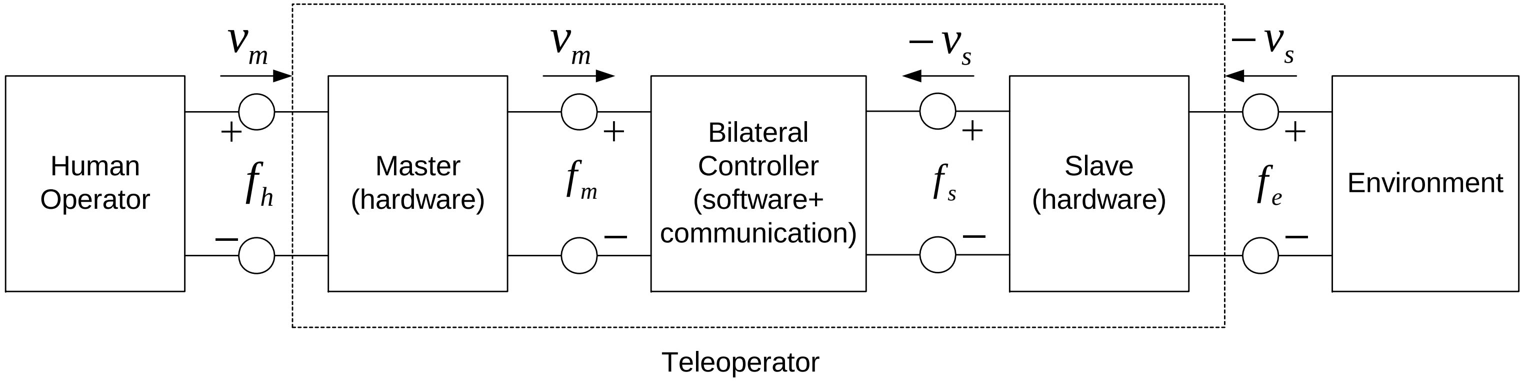
- Energy is absorbed by both ports
  - No need to activate any PC
- Energy is produced by one port
  - Need to activate only one PC at the active port
- Energy is produced by both ports
  - Many strategies are possible

$$W(n) = W(n-1) + f_1(n)v_1(n) + f_2(n)v_2(n) < 0$$

due to the damping allocation among the 2 ports such that

$$\alpha_1(n)v_1(n)^2 + \alpha_2(n)v_2(n)^2 = -W(n)$$

# Real-time Availability Should be Checked for Designing PO/PC



Passivity Observer

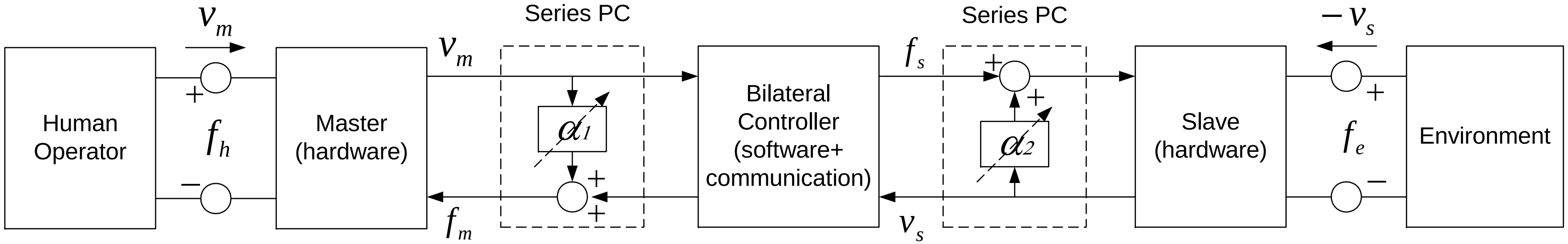
$$E_{obsv}(n) = \Delta T \sum_{k=0}^{n} \left( f_m(k) v_m(k) + f_s(k) v_s(k) \right) = \Delta T \cdot W(n)$$

# Select Type of PC with Causality

- Physical energy is transferred to a physical system through the place where an actuator is placed

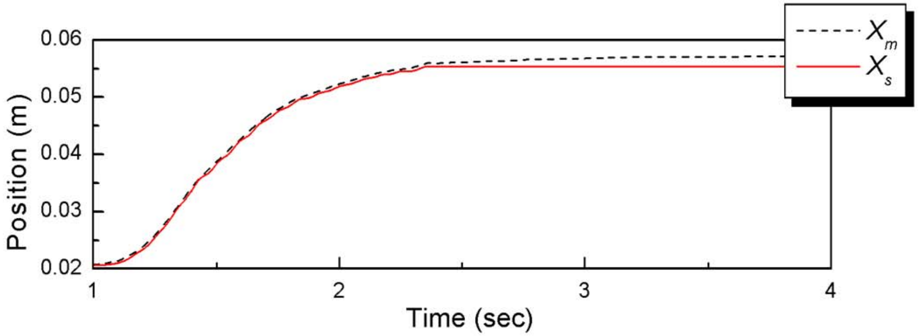
- Motor has admittance causality

  ➡ Bilateral controller has impedance causality

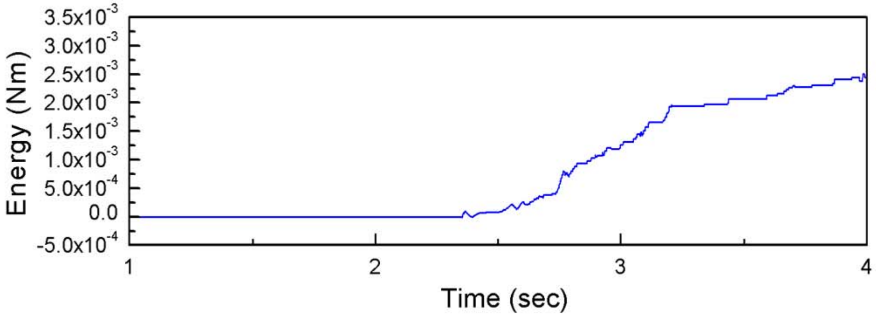


# Experimental Video Clip

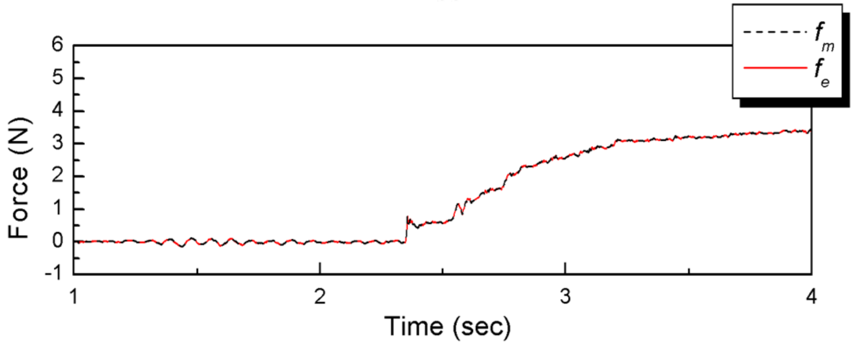
# Hard Contact with Low Velocity



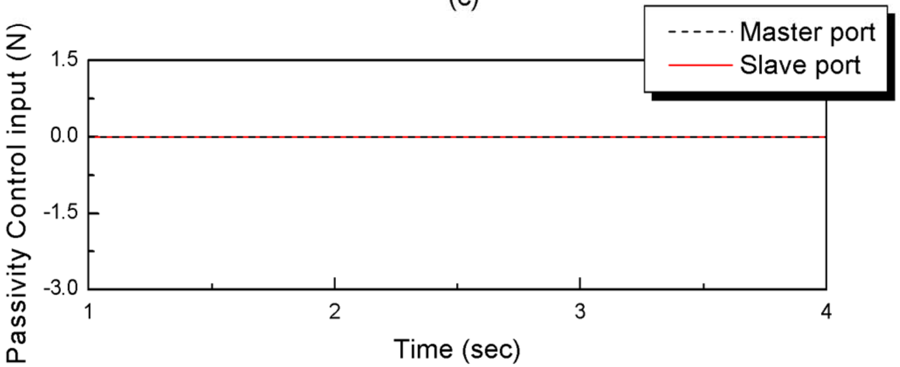
(a)



(c)



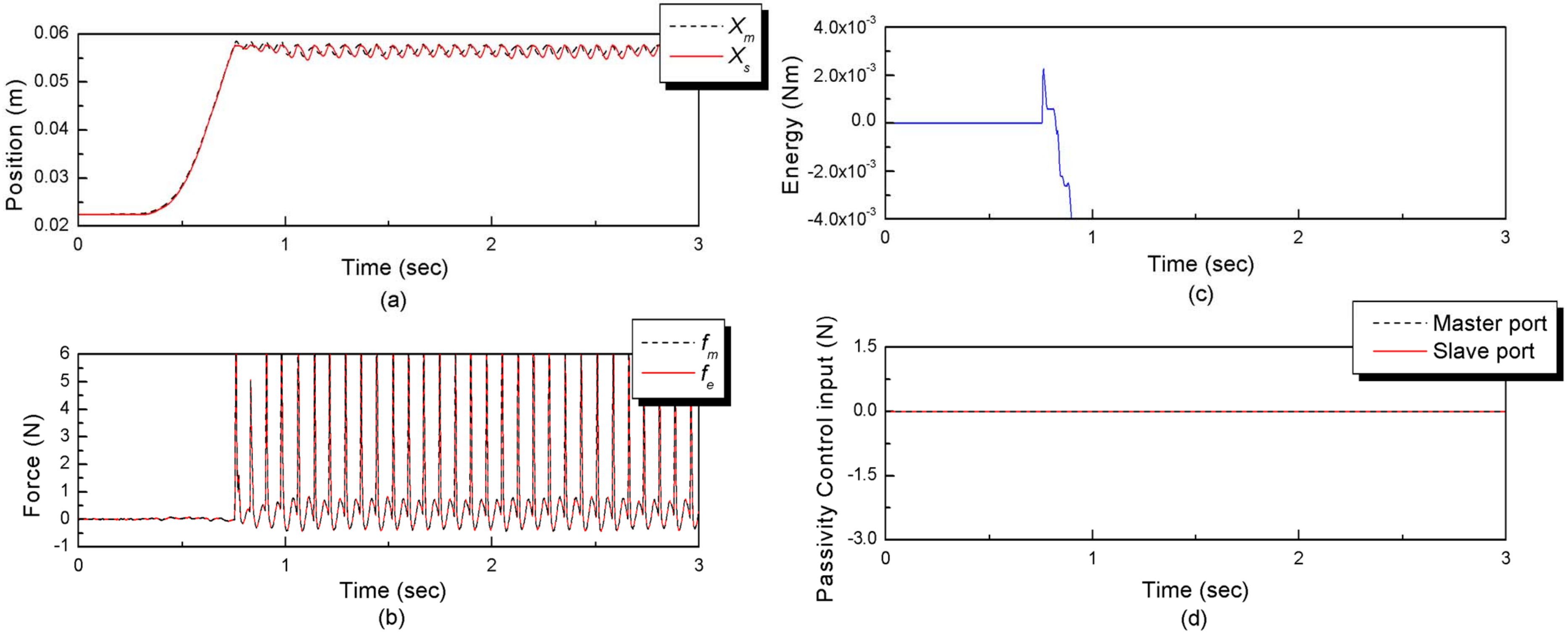
(b)



(d)

- Stable contact can be achieved even the Environment has high stiff

# Hard Contact with High Velocity and without PC



(a)

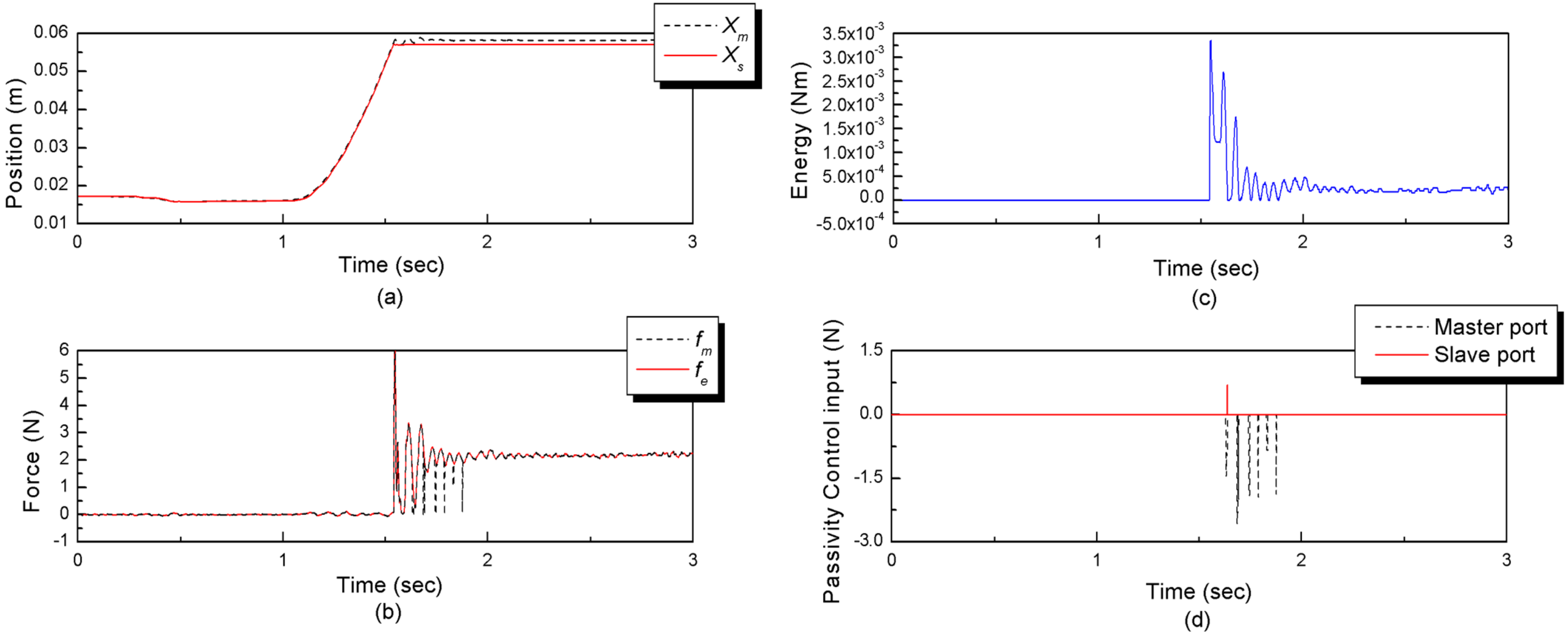
(c)

(b)

(d)

- Contact is unstable
- PO<0

# Hard Contact with High Velocity and with PC



(a)

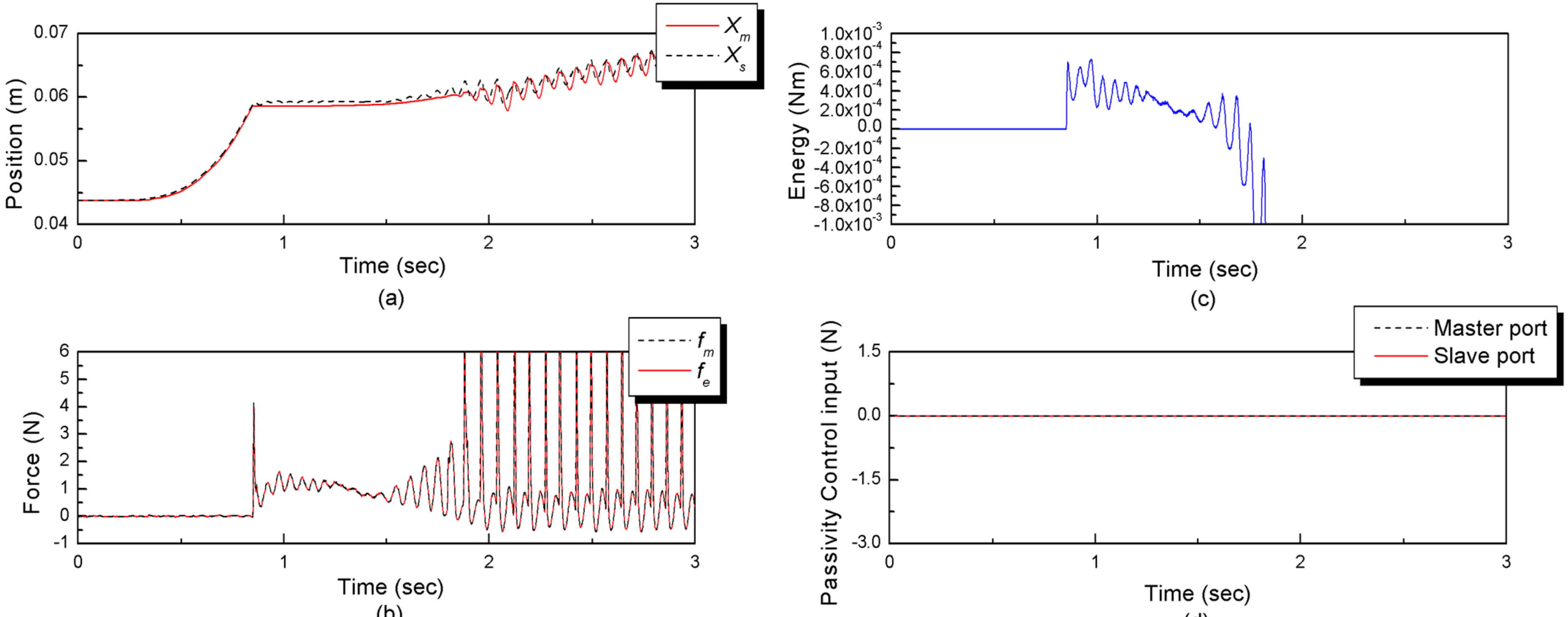
(c)

(b)

(d)

- ➢Stable contact is achieved with about 7 bounces
- ➢Transmitted force is modified by the PC if it is needed

# Following the Slanted Hard Wall without PC



(a)

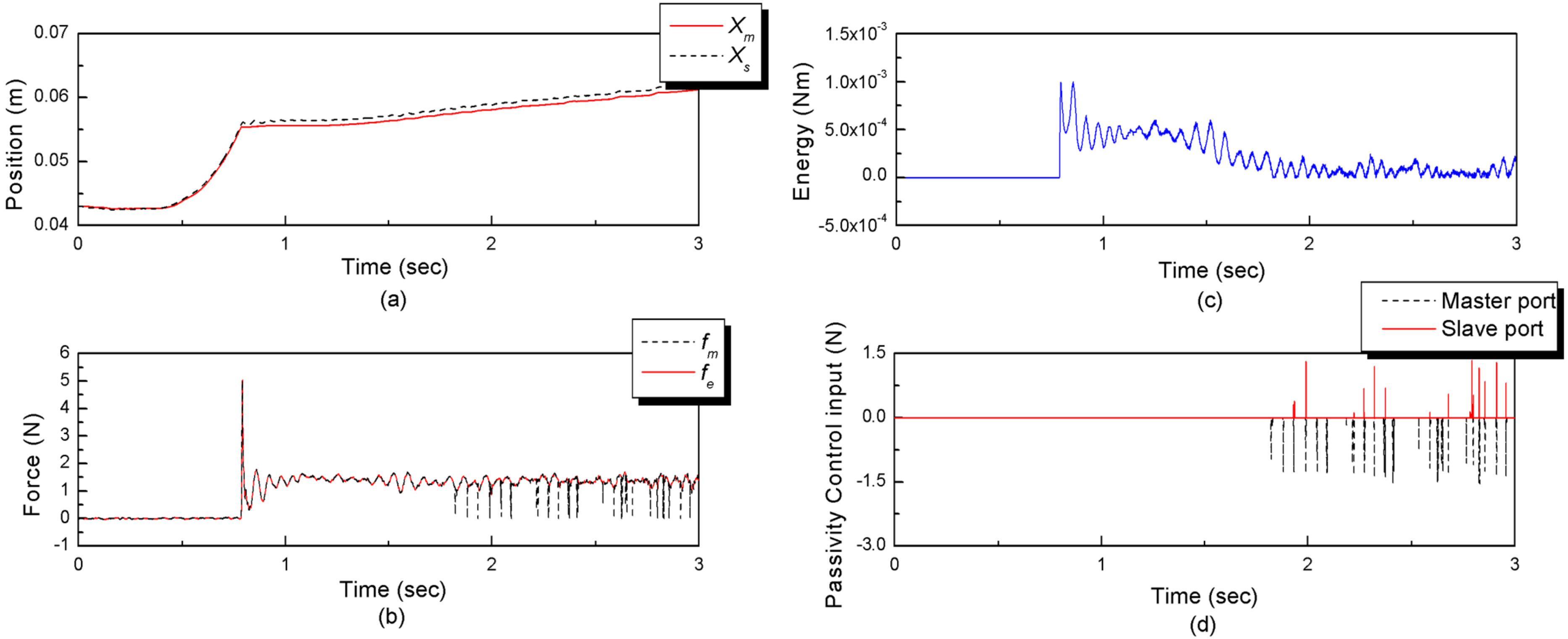
(c)

(b)

(d)

- ➢Contact become unstable during the following
- ➢PC become negative

# Following the Slanted Hard Wall with PC



(a)

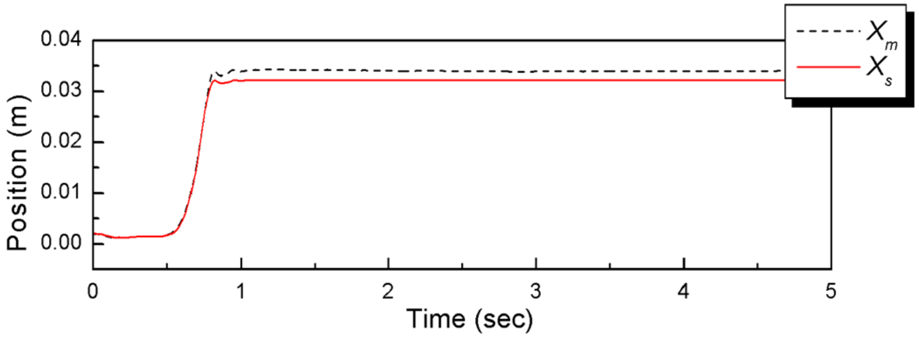
(b)

(c)

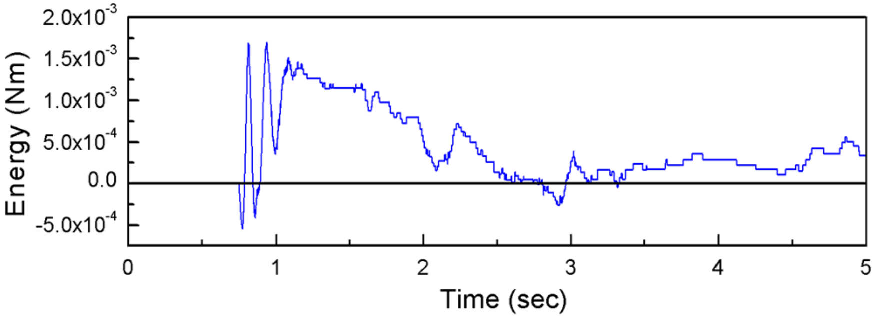
(d)

- ➢Following is stable
- ➢PC output consists of noise-like signal during low velocity

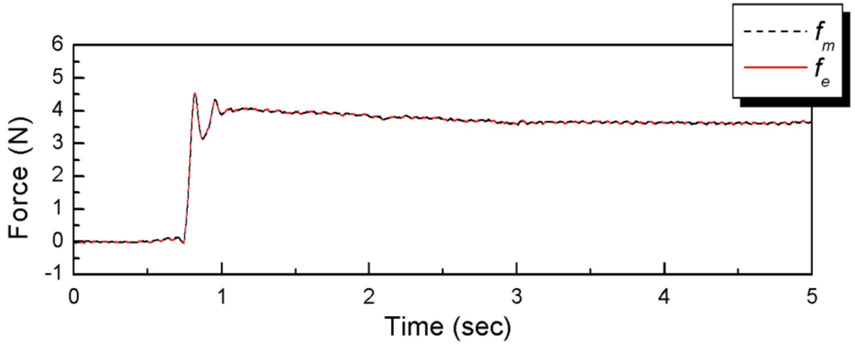
# Contact with Soft Sponge with High Velocity without PC



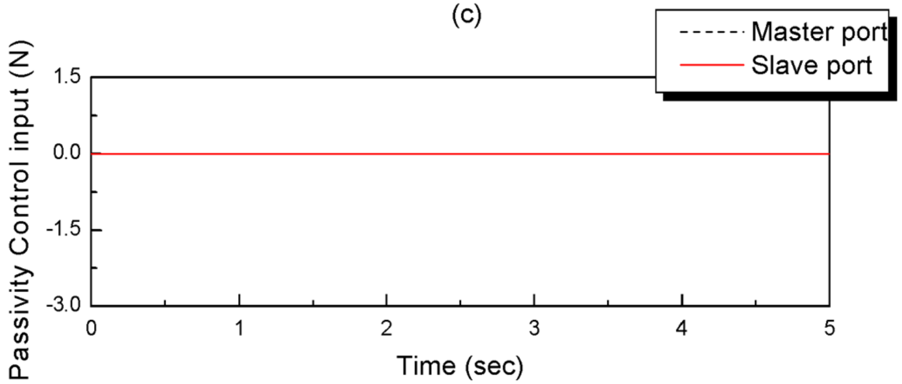
(a)



(c)



(b)



(d)

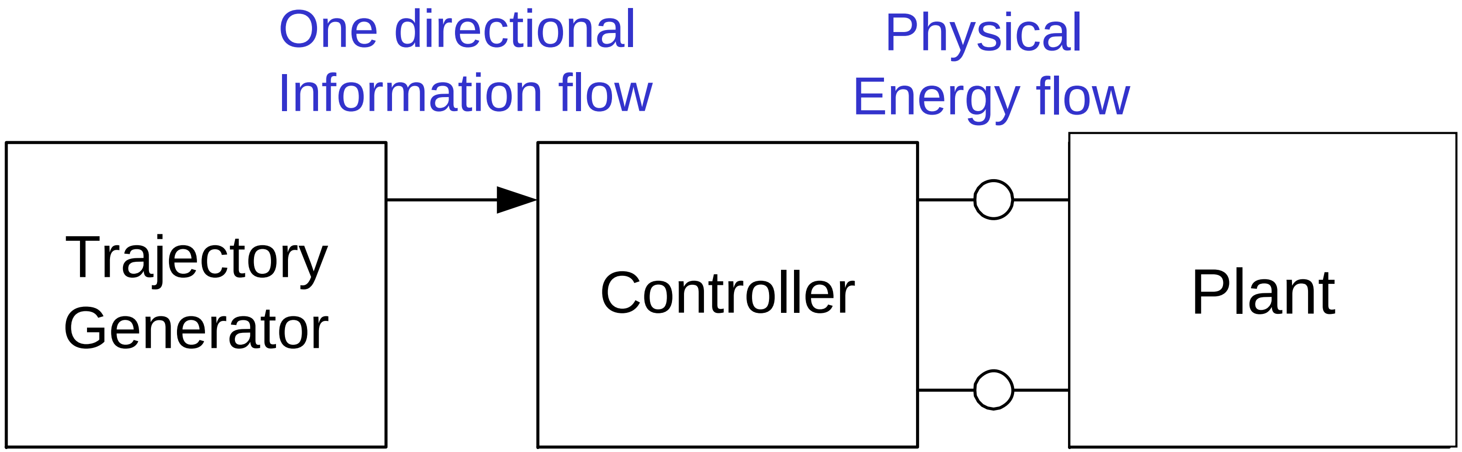
- ➢Even contact is stable, PO crosses to negative value
- ➢Need to consider external dissipation

# Extension of the Time Domain Passivity Control to General Motion Control Systems

1. Network Modeling
2. Implementation Issues
3. Simulation Results

# Conventional View of General Control Systems

- Network model with energy flow is required
- The PO/PC is based on energy monitoring



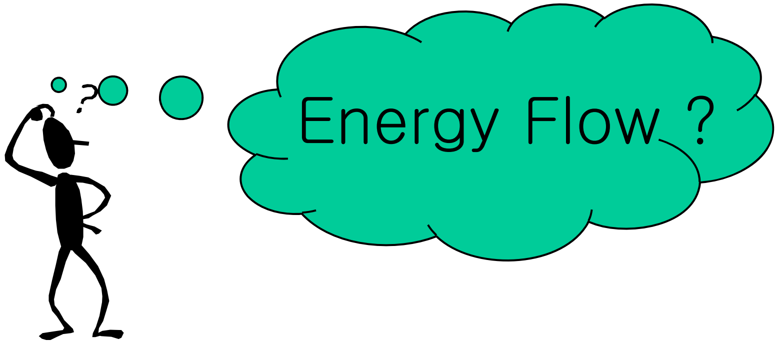
One directional Information flow

Physical Energy flow

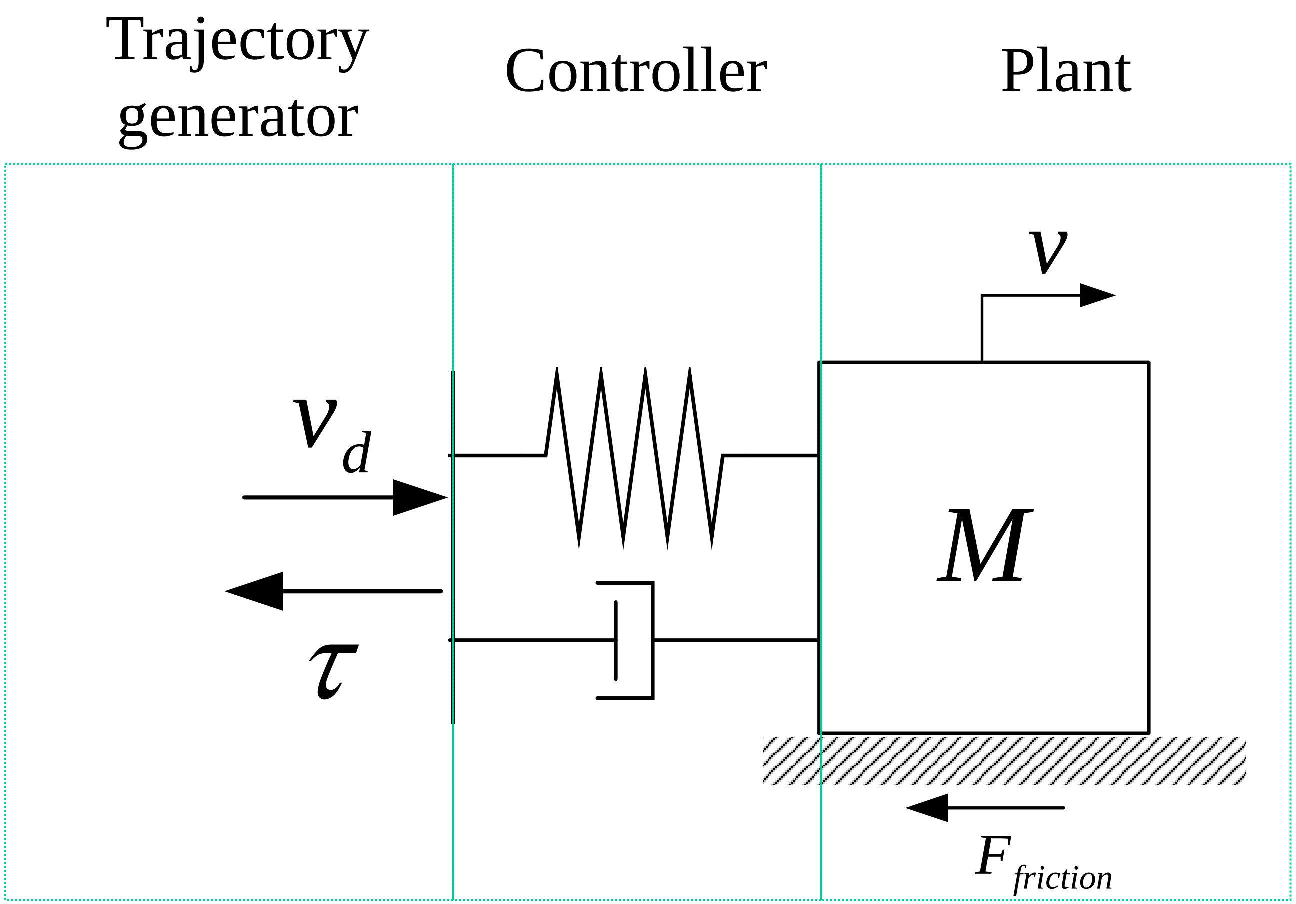
Trajectory Generator

Controller

Plant



# Physical Analogy of Motion Control Systems

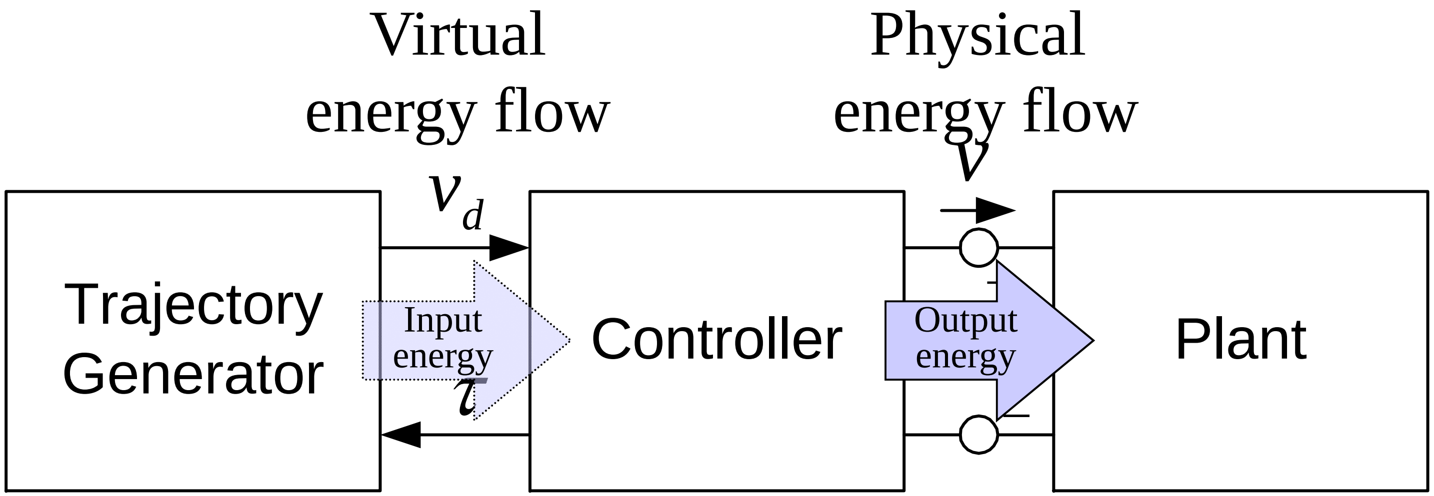


Trajectory generator

Controller

Plant

# Network Model of Motion Control Systems



Virtual energy flow

Physical energy flow

Trajectory Generator

$v_d$

$\tau$

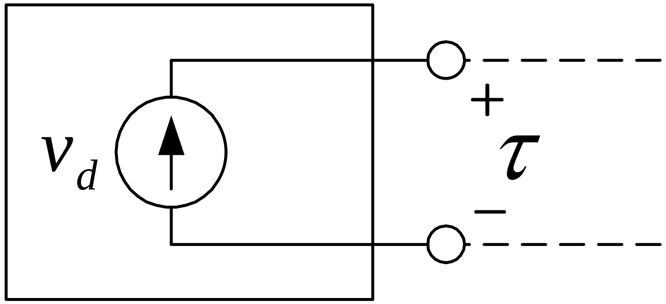
Input energy

Controller

$v$

Output energy

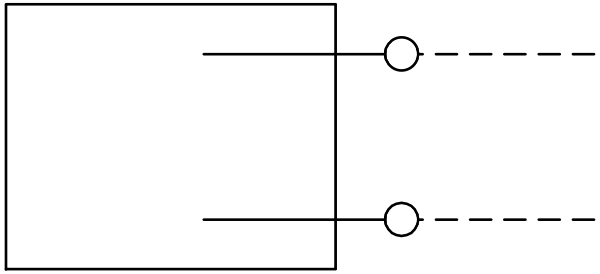
Plant



Tracking controller

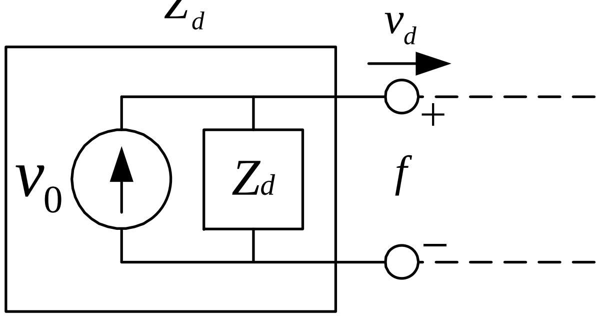
# Generality of the Network Representation

$$v_d = 0$$

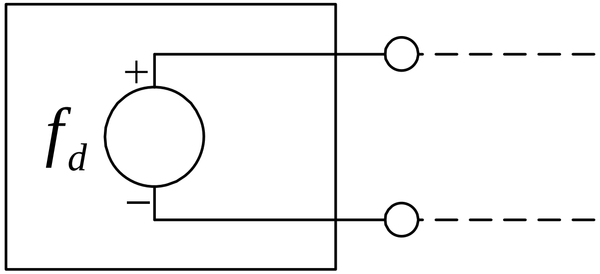


Regulator

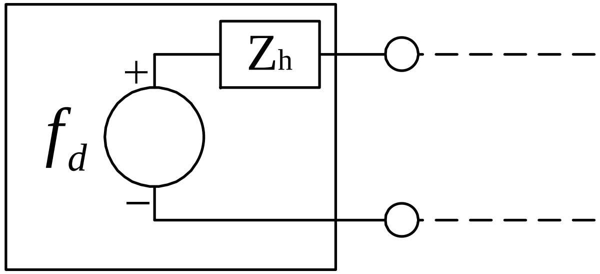
$$v_d = -\frac{1}{Z_d} f + v_0$$



Impedance/Admittance Controller

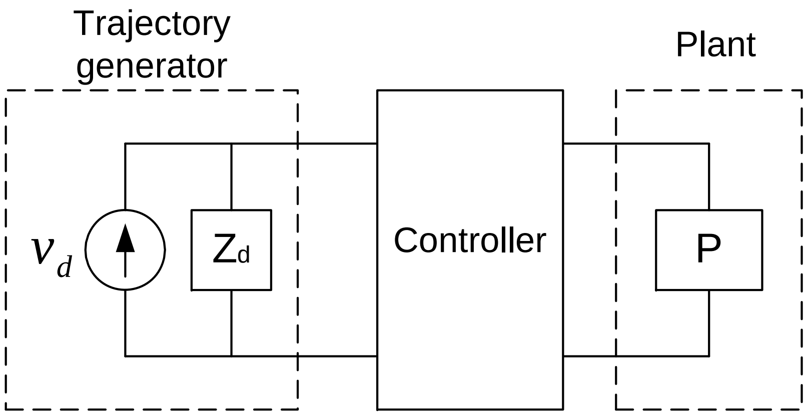


Force controller

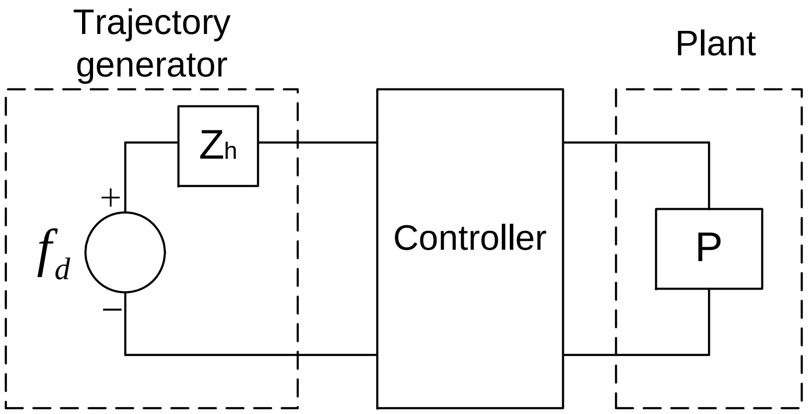


Human supervisory controller

# Stability Condition



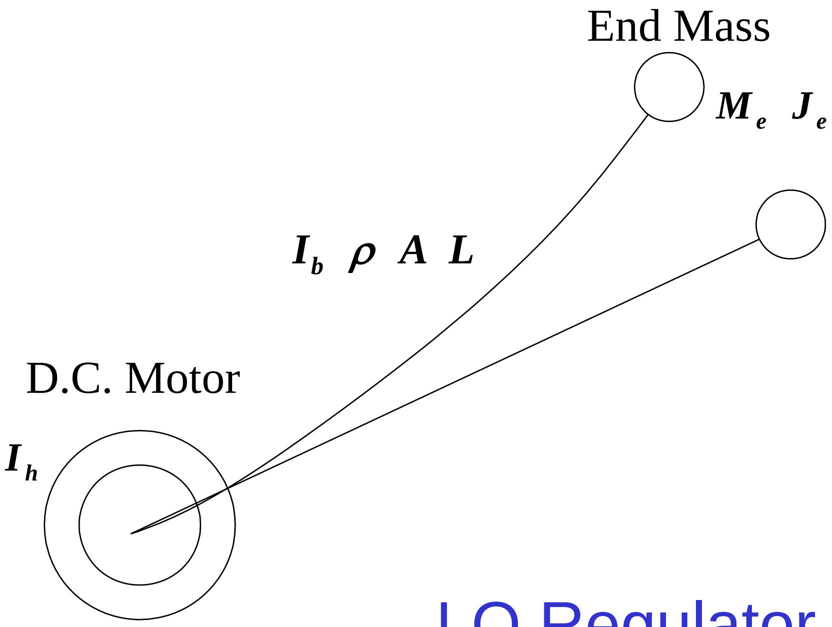
Motion or Impedance/admittance



Force or human supervisory

- Input energy depend on connected network
- Connected network is passive ➡ marginally passive
- Plant is uncertain zero ~ inf. impedance range
- Controller 2-port should be passive

# Motion Control of Single-link Flexible Manipulator



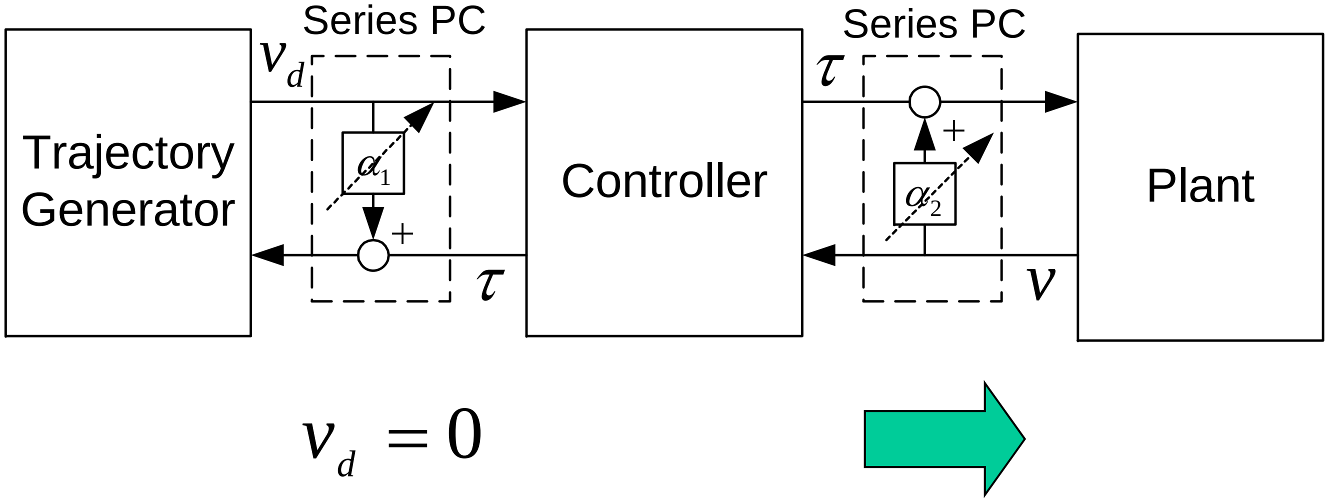
Manipulator model
(Kwon and Book,1994)

-70% end-mass perturbation
+50% damping perturbation
-30% stiffness perturbation

LQ Regulator for nominal model
+
Passivity Controller

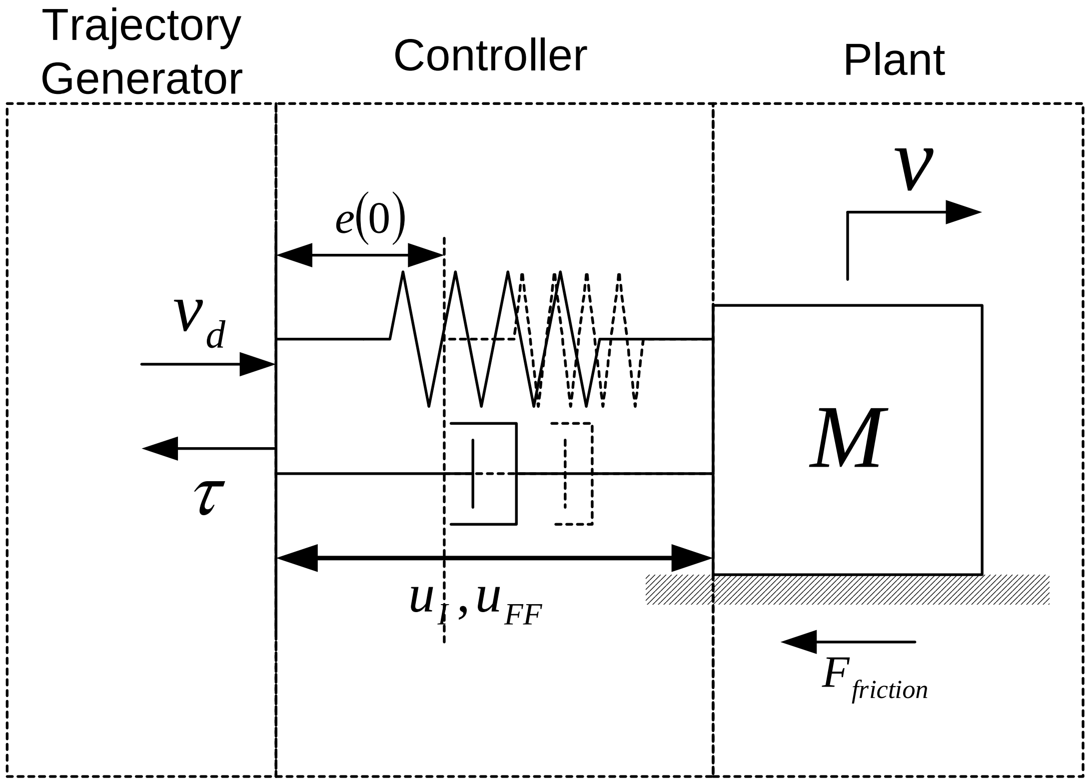
# Design PO/PC with Causality

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



$$v_d = 0$$

# Meaning of Initial Energy Storage $E(0)$



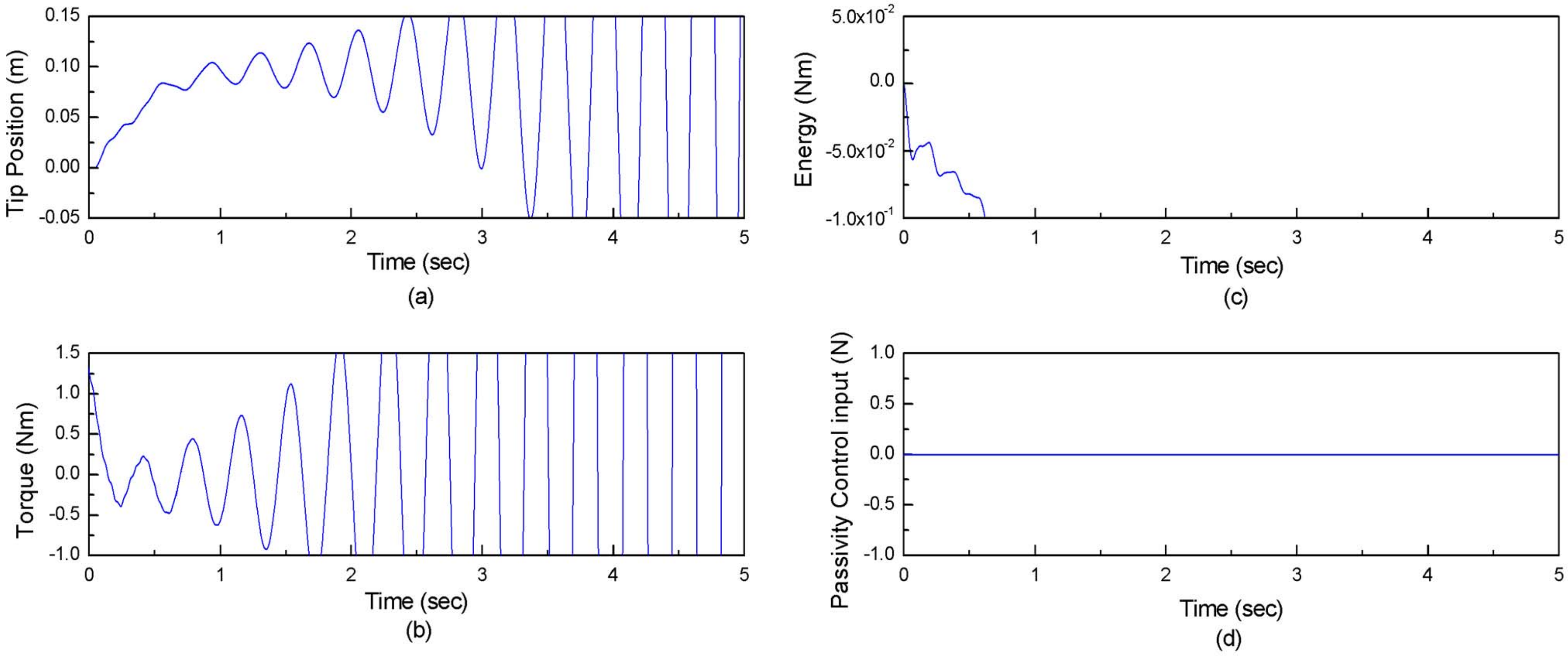
**$e(0)$ : Initial position error**

**$K_p$ : Proportional gain**

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

***Energy bound of regulation controller***

# Nominal LQ Regulator without PC

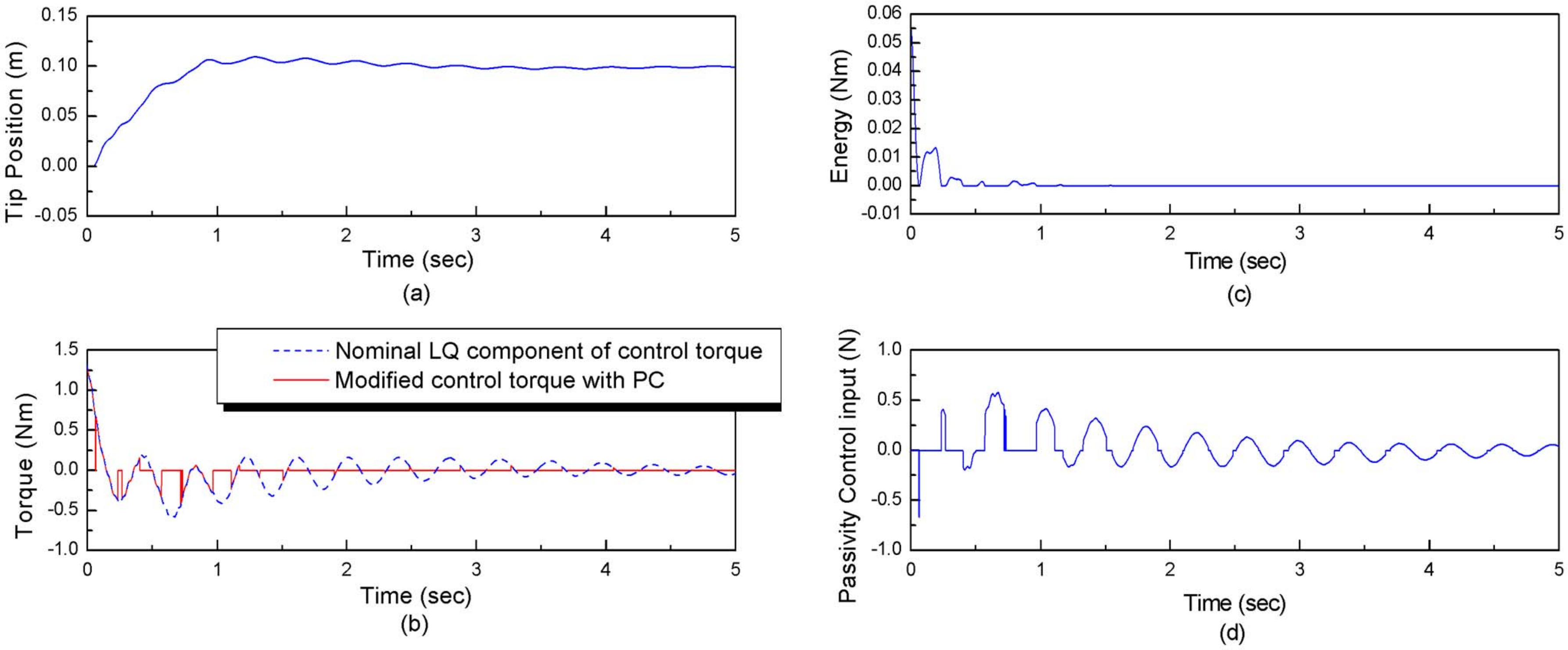


(a) (c)

(b) (d)

- ➢Regulation is unstable

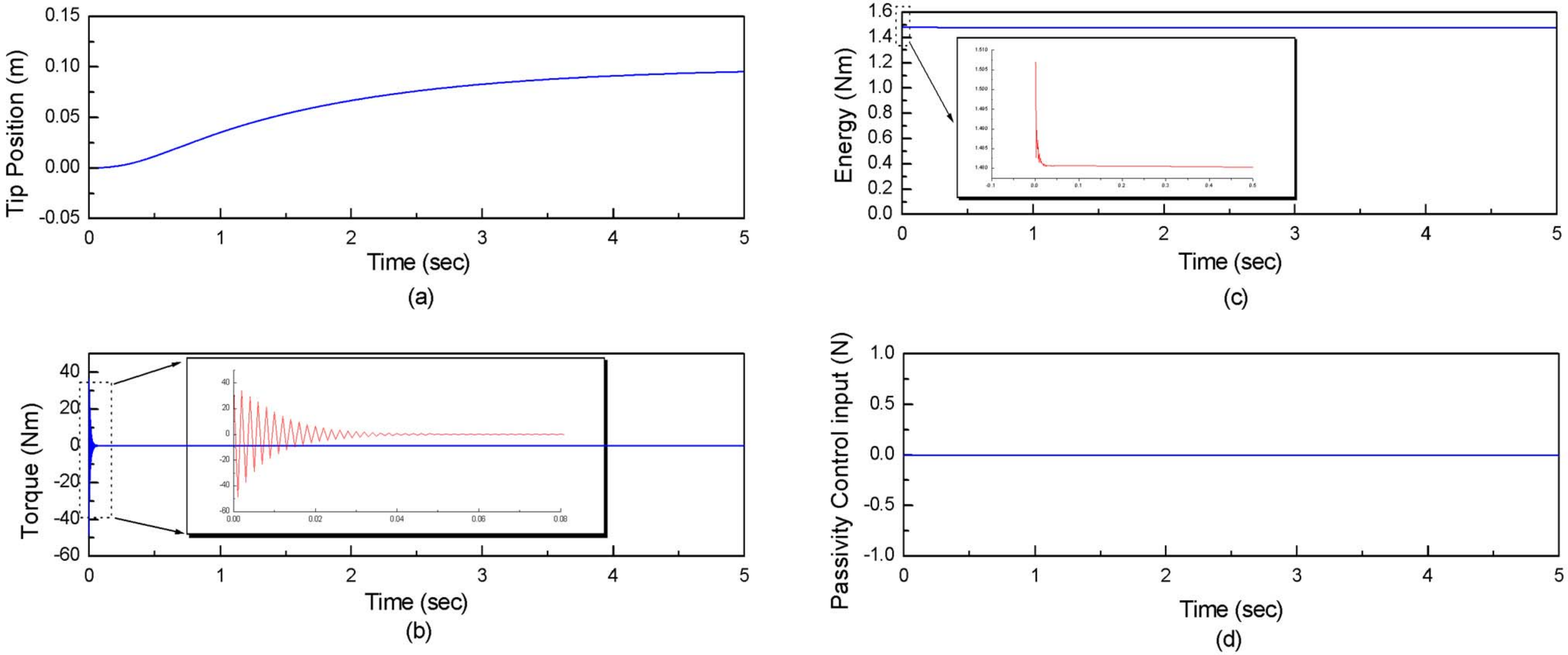
# Nominal LQ Regulator with PC



(a) (b) (c) (d)

- ➢Stable regulation is achieved
- ➢During the rise time, PC is only activated several time (E(0)=0.055)

# Polytopic Robust LQ regulator



(a)

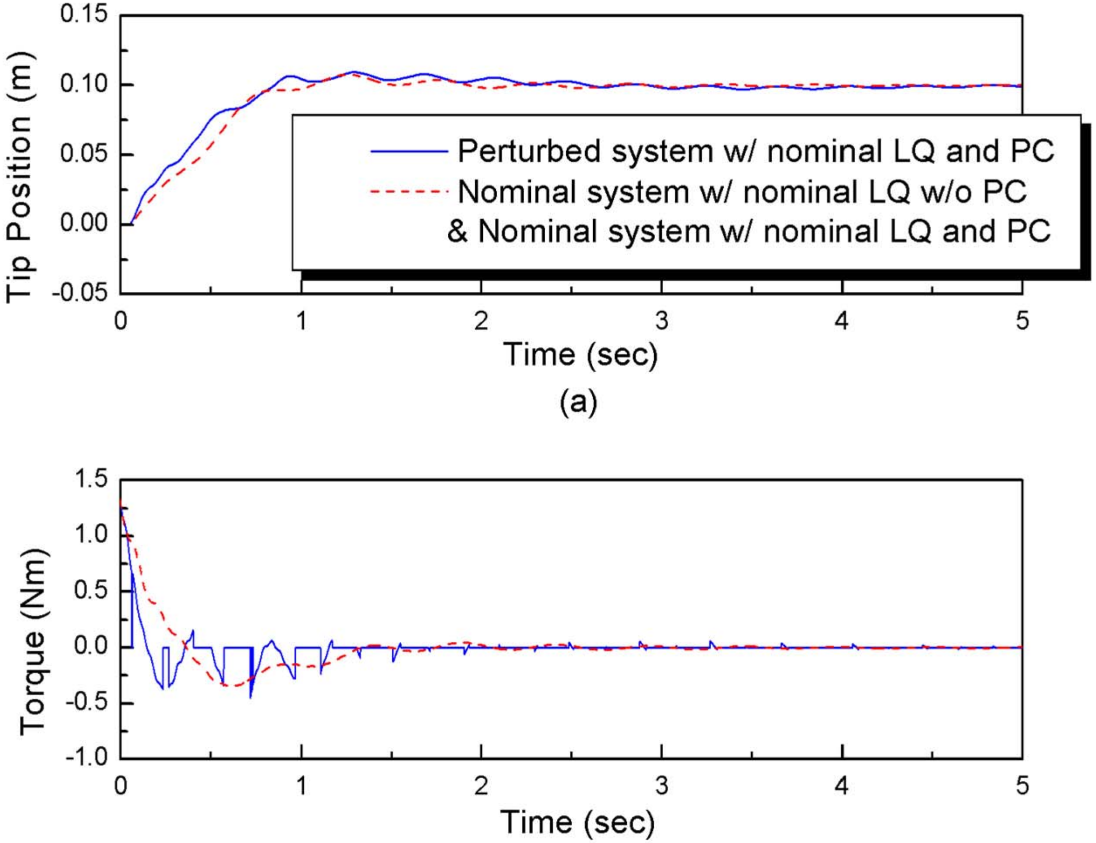
(c)

(b)

(d)

- ➢Controller remain passive (E(0)=1.51), the response is very slow
- ➢Controller require large amount of control input

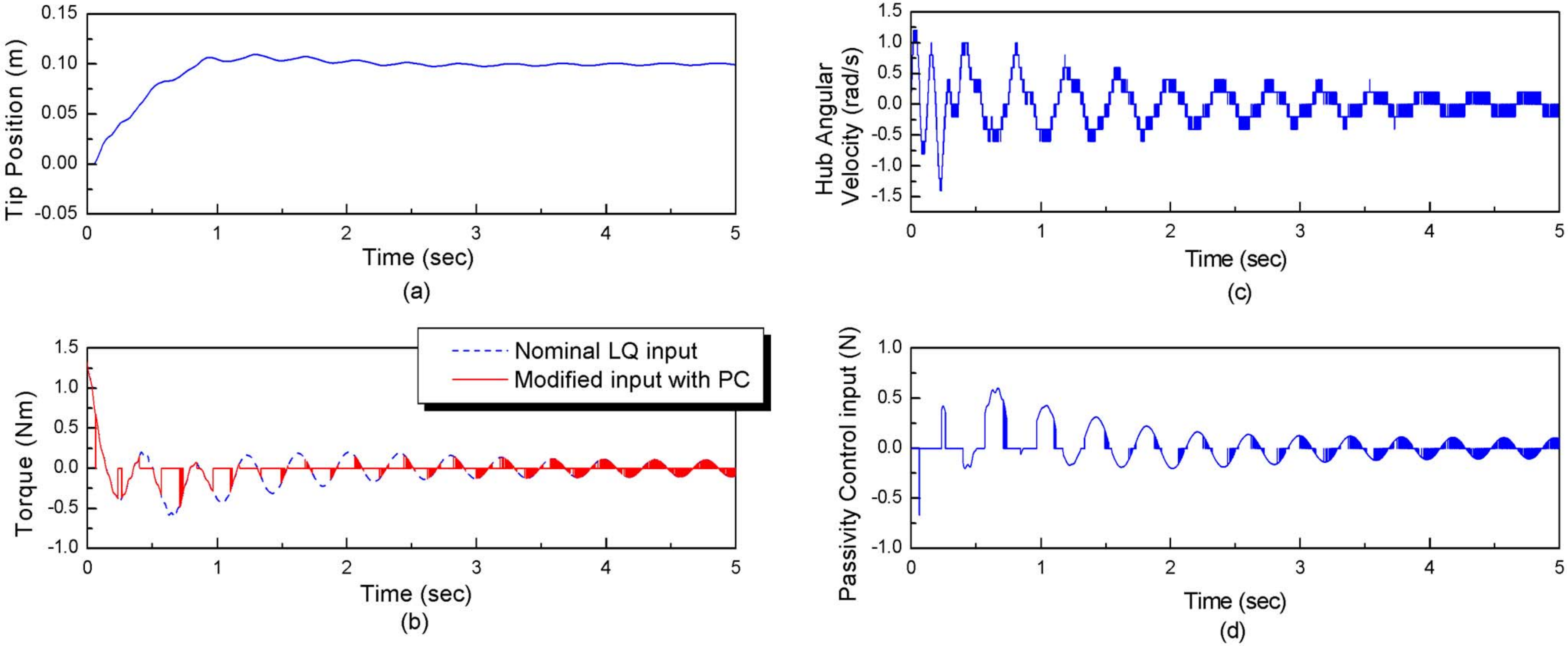
# Comparison of PC Approach with Nominal LQ Controller w/o Perturbation



(a)

(b)

# Nominal LQ Regulator when Quantization effect is added



(a) (b) (c) (d)

- ➢Performance is slightly degraded
- ➢Noise PC output during a period of low velocity

# Control of Flexible Manipulator with Non-collocated Feedback

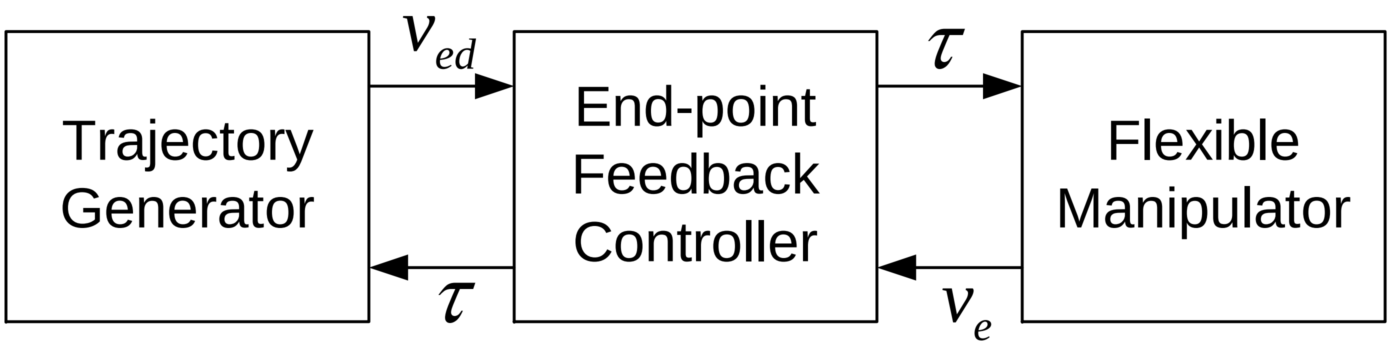
1. Network Modeling
2. Implementation Issues
3. Simulation Results

# Control of Non-minimum Phase System

- Interesting point is tip-position
  - Tip-position feedback can increase the control performance
- Non-collocated system
  - Tip-position output, joint torque input
- Non-minimum phase system
  - Small increment of controller gain and system parameter perturbation can easily make the closed-loop system unstable

# PO/PC can not be Applied to an Active Plant

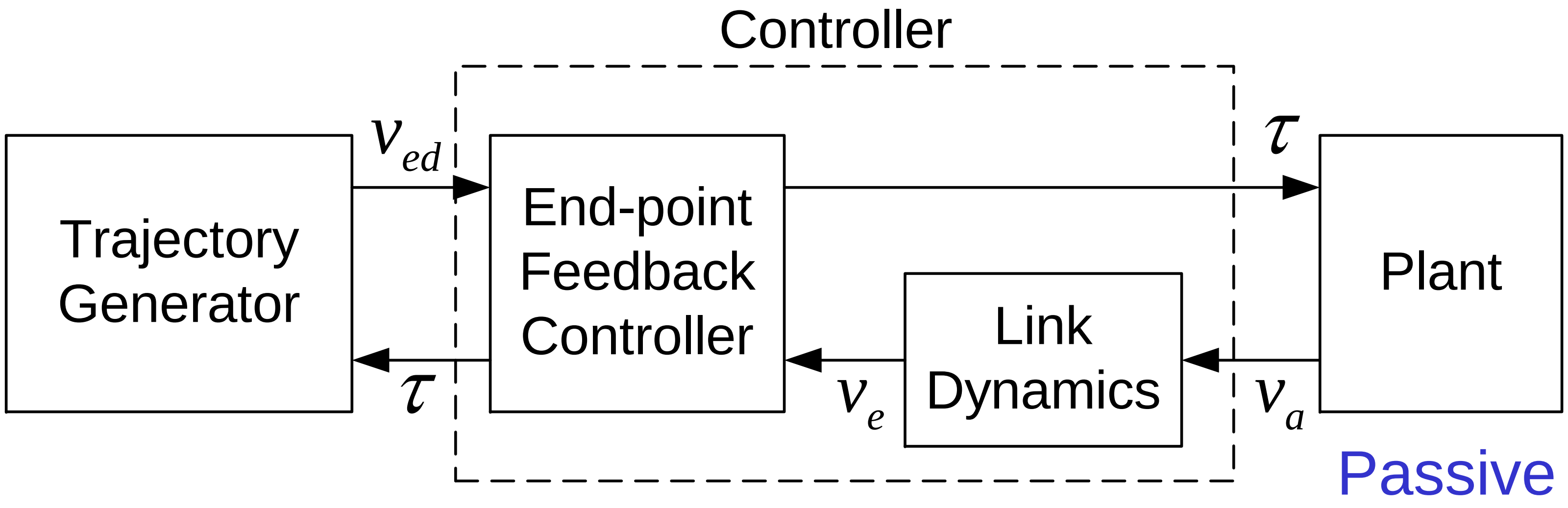
- If the plant is active, the overall system may not be passive even the controller remains passive



Active

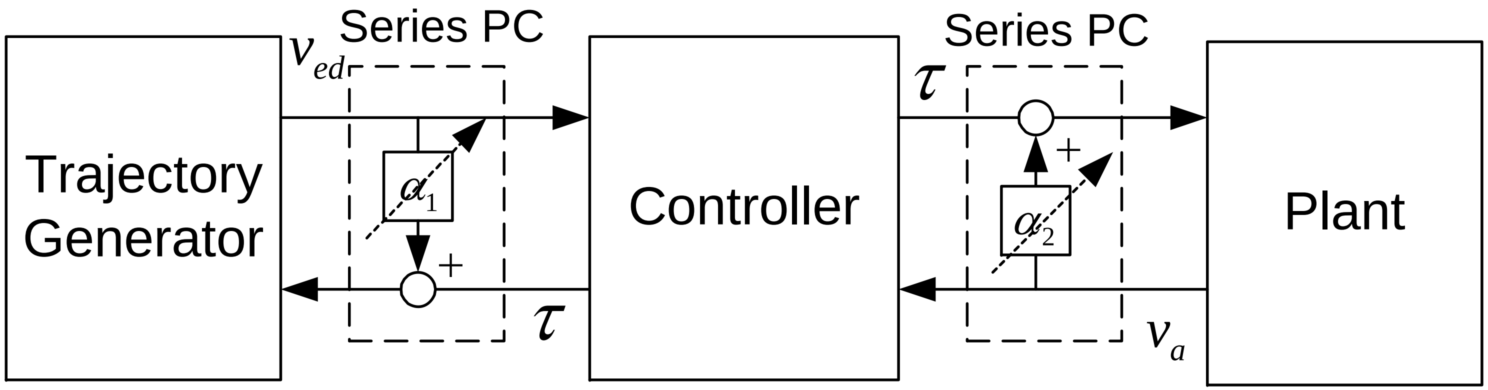
# Change to Suitable Model to PO/PC Approach

- Physical energy is transferred to a physical system through the place where an actuator is placed

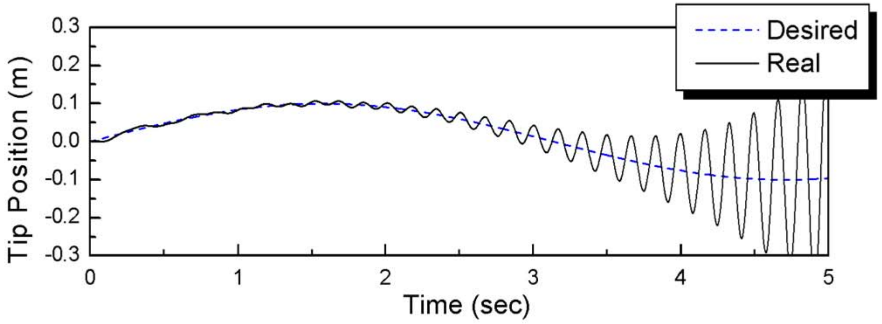


# Designing the PO/PC

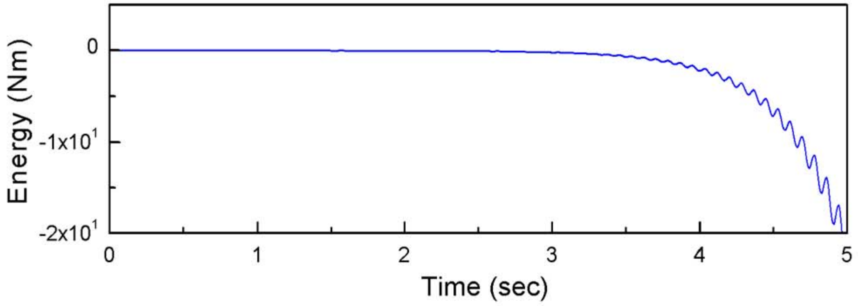
- Two Impedance type PCs



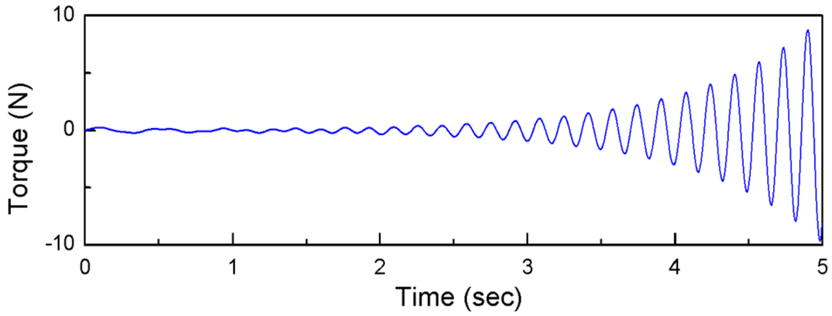
# Tip-position PD Control without PC



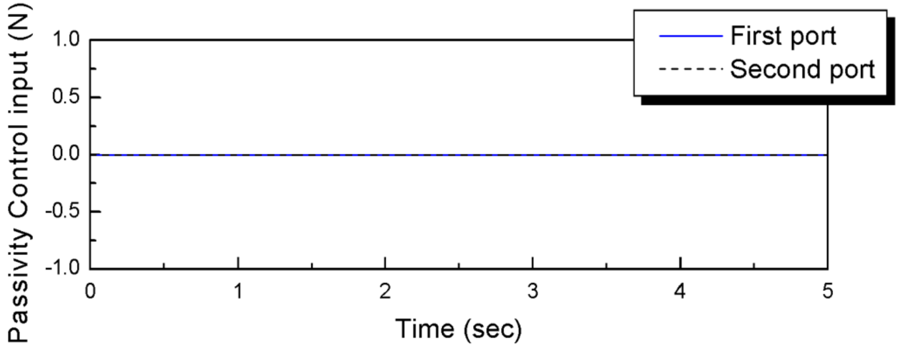
(a)



(c)



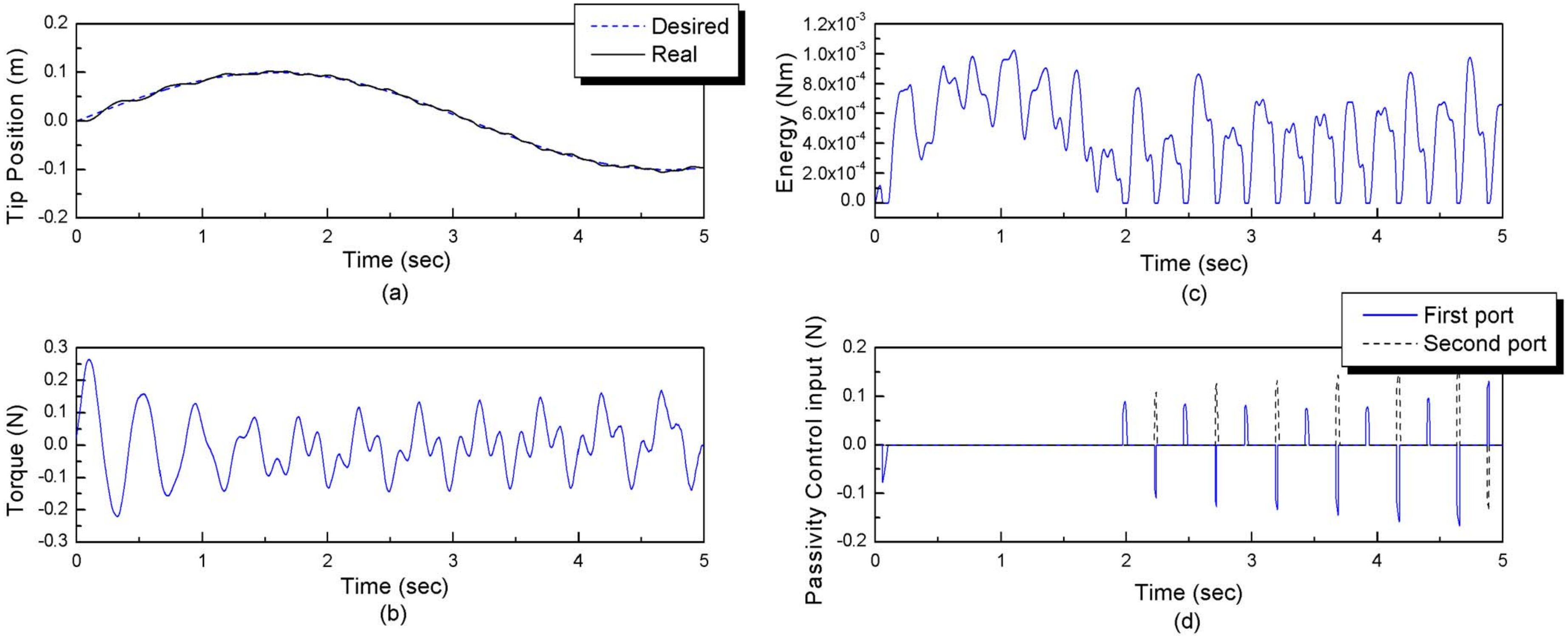
(b)



(d)

- ➢Control is unstable
- ➢PO<0

# Tip-position PD Control with PC



- ➢Stable tracking is achieved
- ➢PC is activated only it is required