Control of Telerobotic Systems

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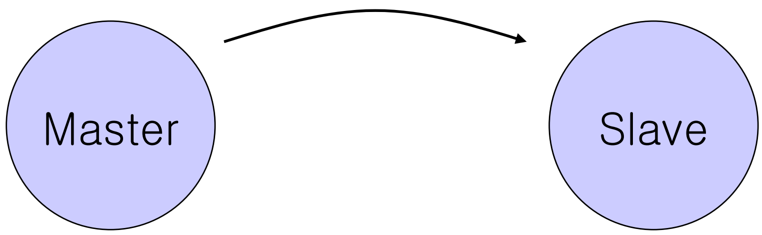
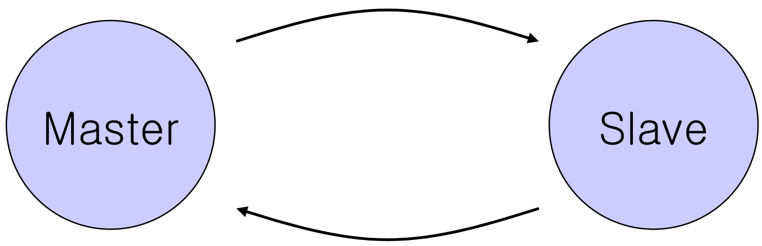
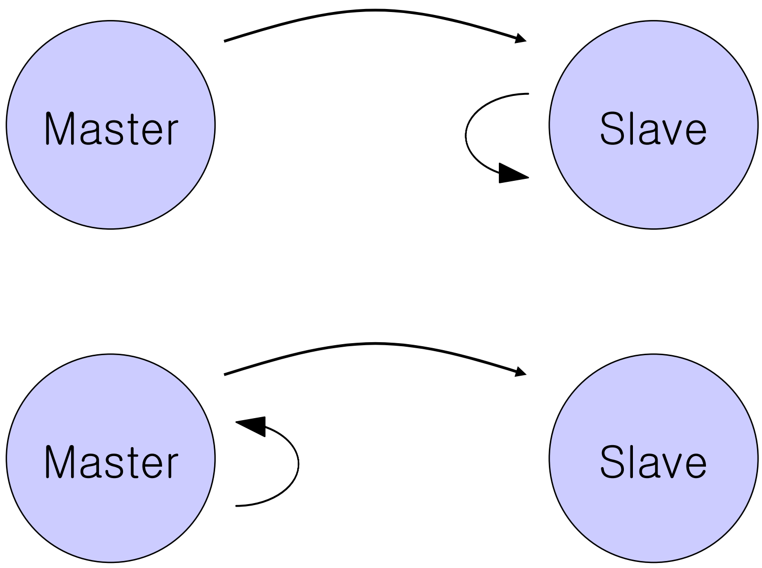
Unilateral vs. Bilateral

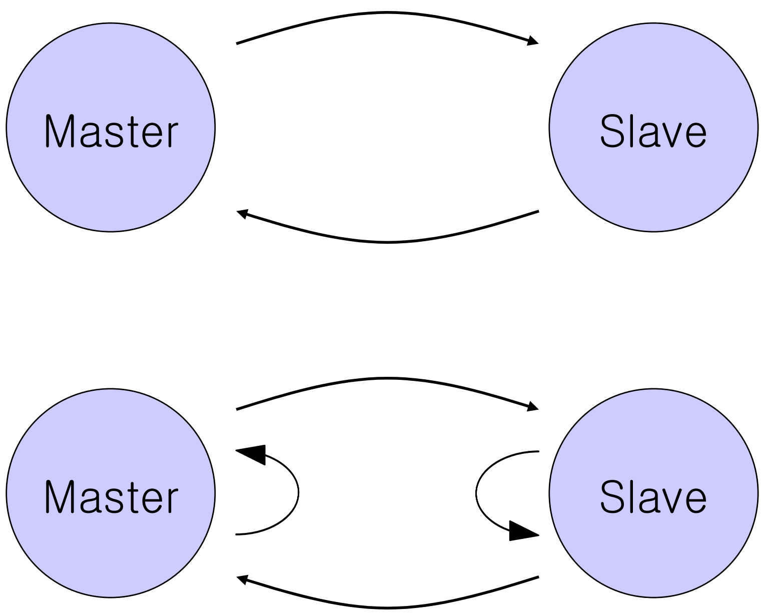




Unilateral Control



Bilateral Control



Control Objectives of Bilateral Control

1. Ideal response

Two Aspects in Control of Teleoperator

- Performance
  - Make the operator feel as if he/she directly interact with the remote environment
- Stability
  - Endure stable operation under wide variety of operating conditions

Ideal Teleoperator [Hannaford, 1989]

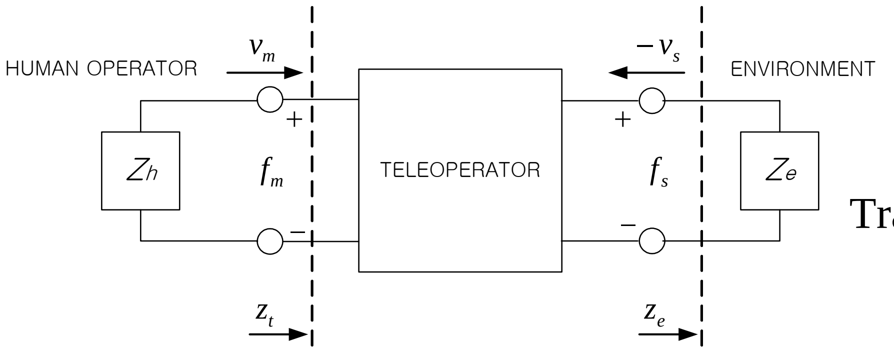
The hybrid two-port network model of teleoperator

Hybrid matrix

$$\begin{bmatrix} f_m \\ -v_s \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} v_m \\ f_s \end{bmatrix} \quad h = \begin{bmatrix} \text{Input impedance} & \text{Force scale} \\ \text{- Velocity scale} & \text{output admittance} \end{bmatrix}$$

$$h_{ideal} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$$

Transparency [Lawrence, 1993]



$$f_s = Z_e v_s$$

$$f_m = Z_t v_m$$

Transparency condition

$$Z_t = Z_e$$

The essential desire is to provide a faithful transmission of signals (positions, velocities, forces) between master and slave to couple the operator as closely as possible to the remote task.
Ideally, the teleoperation system would be completely transparent, so operators feel that they are directly interacting with the remote task.

Ideal response : ideal kinesthetic coupling

[Yokokohji, 1994]

- ***Ideal response I*** : the position responses by the operator's input are identical, whatever the object dynamics is.

$$x_m = x_s$$

- ***Ideal response II*** : the force responses by the operator's input are identical, whatever the object dynamics is.

$$f_m = f_s$$

- ***Ideal response III*** : both the position responses and the force responses by the operator's input are identical respectively, whatever the object dynamics is.

$$x_m = x_s \quad \& \quad f_m = f_s$$

Arbitrarily position/force scaling [Ryu, 1999]

$$x_s = \lambda_p x_m$$

$$\lambda_f f_s = f_m$$

Position/Force Matching vs. Impedance Matching

Position/Force matching

$$x_s = x_m$$

$$f_s = f_m$$

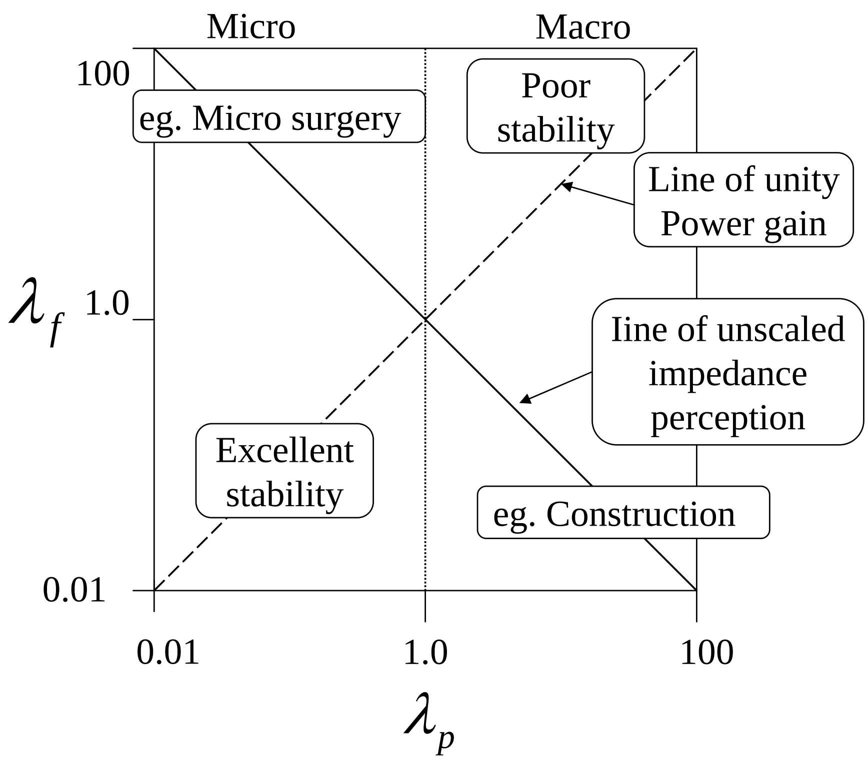
Impedance matching

$$Z_t = Z_e$$

Position/Force matching $\rightarrow$ Impedance matching

Position/Force matching $\not\leftarrow$ Impedance matching

Characteristics on Scaling



$$x_s = \lambda_p x_m$$

$$f_s = \frac{1}{\lambda_f} f_m$$

Architectures of Bilateral Control

1. P/P
2. P/F
3. F/F
4. PF/PF
5. Local Force Feedback

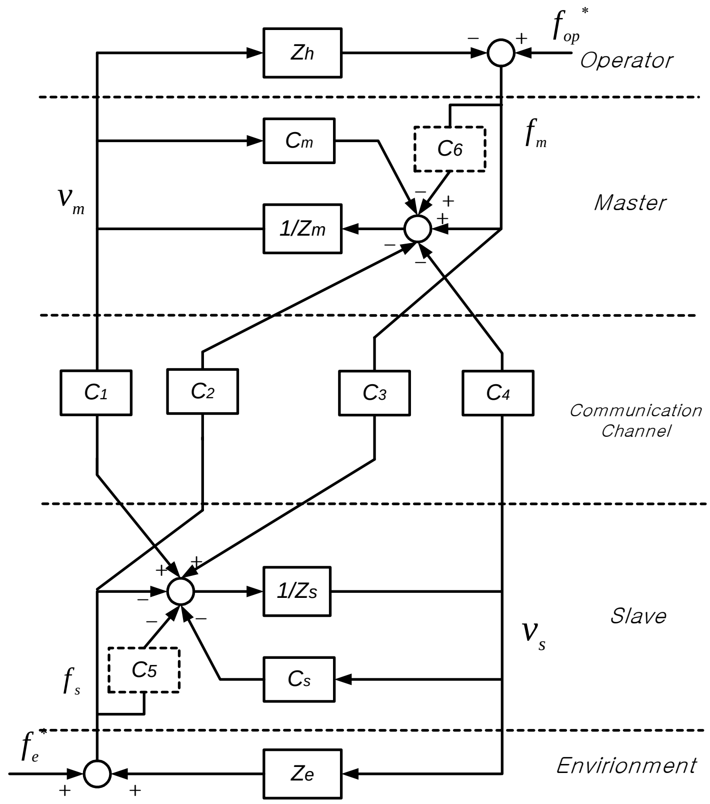
General Bilateral Control Architecture

$$\tau_m = \begin{bmatrix} K_{mpm} + K'_{mpm}\frac{d}{dt} + K''_{mpm}\frac{d^2}{dt^2} & K_{mfm} \end{bmatrix} \begin{bmatrix} x_m \\ f_m \end{bmatrix} - \begin{bmatrix} K_{mps} + K'_{mps}\frac{d}{dt} + K''_{mps}\frac{d^2}{dt^2} & K_{mfs} \end{bmatrix} \begin{bmatrix} x_s \\ f_s \end{bmatrix}$$

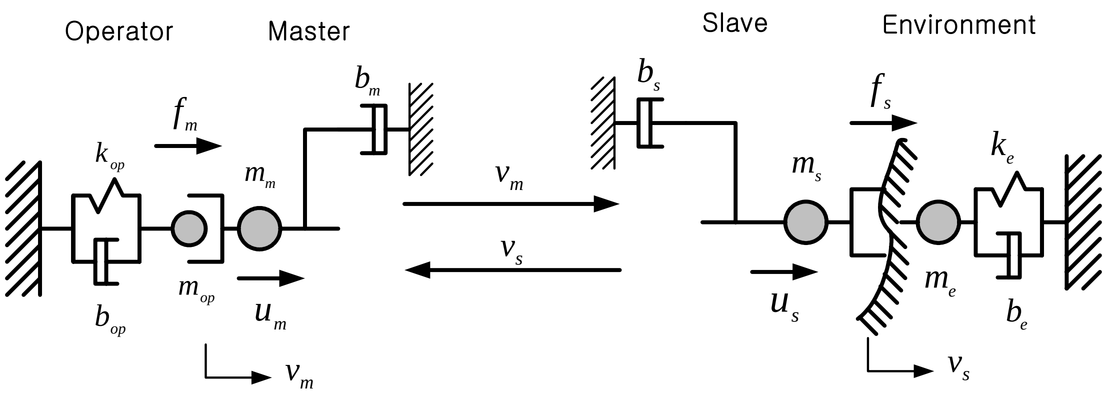
$$\tau_s = \begin{bmatrix} K_{spm} + K'_{spm}\frac{d}{dt} + K''_{spm}\frac{d^2}{dt^2} & K_{sfm} \end{bmatrix} \begin{bmatrix} x_m \\ f_m \end{bmatrix} - \begin{bmatrix} K_{sps} + K'_{sps}\frac{d}{dt} + K''_{sps}\frac{d^2}{dt^2} & K_{sfs} \end{bmatrix} \begin{bmatrix} x_s \\ f_s \end{bmatrix}$$

Use all 4 information for control

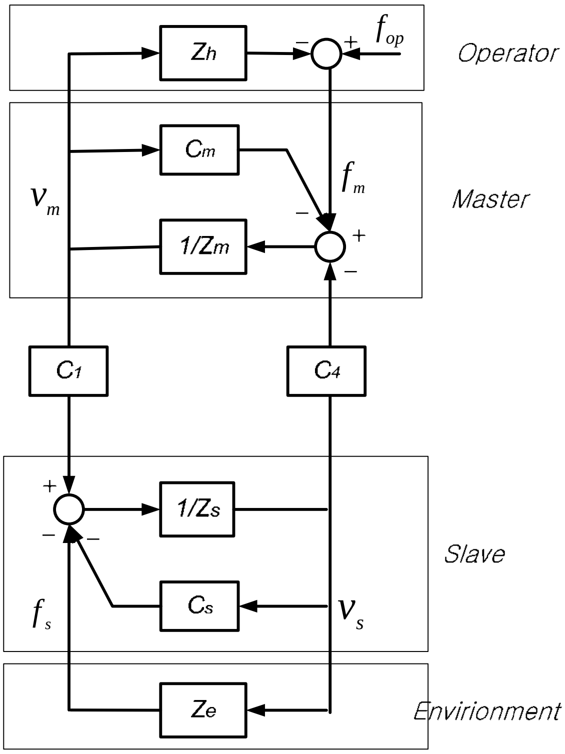
General Structure 4-channel



Position/Position Architecture



Position/Position Architecture



$$Z_h = m_{op} s + b_{op} + \frac{k_{op}}{s}$$

$$Z_m = m_m s + b_m$$

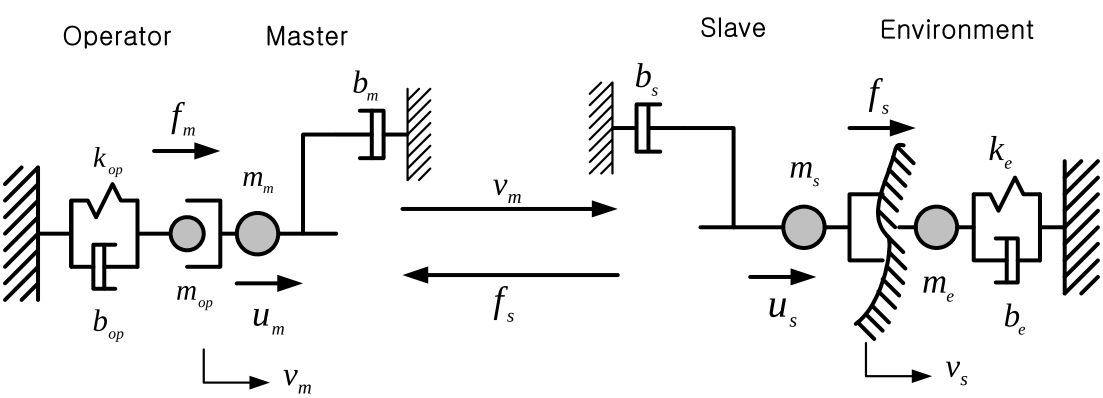
$$C_s = C_1 = B_s + K_s / s$$

$$C_m = -C_4 = B_m + K_m / s$$

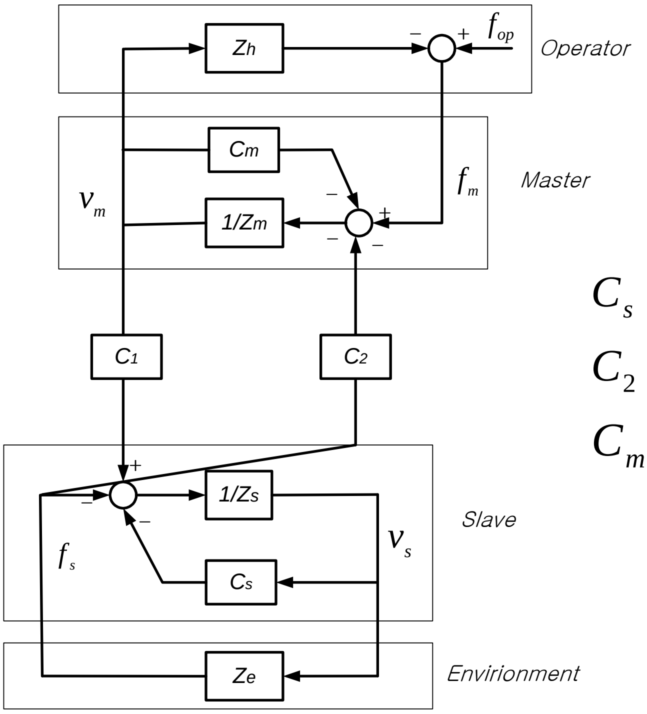
$$Z_s = m_s s + b_s$$

$$Z_e = m_e s + b_e + \frac{k_e}{s}$$

Position/Force Architecture



Position/Force Architecture

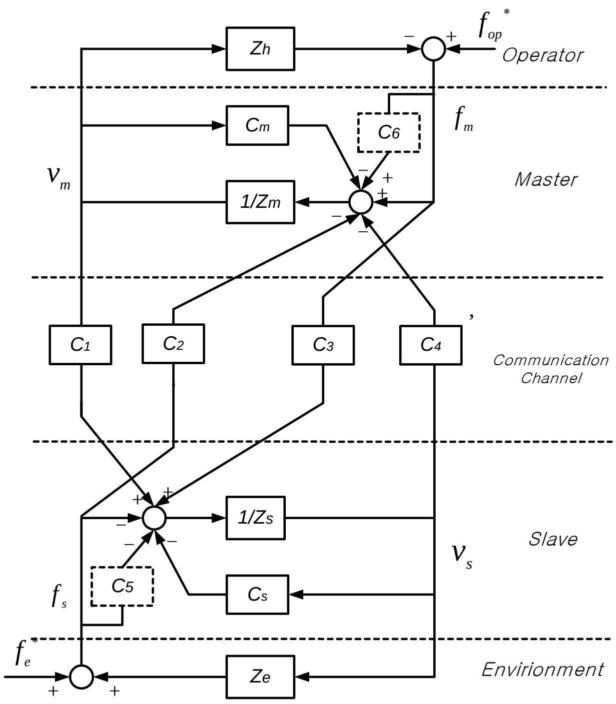


$$C_s = C_1 = B_s + K_s / s$$

$$C_2 = 1$$

$$C_m = B_m$$

General Structure (4-channel)



Position-position architecture :

$C_1 \neq 0, C_4 \neq 0, C_2 = C_3 = 0$

$C_5 = C_6 = 0$

Position-force architecture :

$C_1 \neq 0, C_2 \neq 0, C_3 = C_4 = 0$

$C_5 = C_6 = 0$

Force-position architecture :

$C_3 \neq 0, C_4 \neq 0, C_1 = C_2 = 0$

$C_5 = C_6 = 0$

Force-force architecture :

$C_2 \neq 0, C_3 \neq 0, C_1 = C_4 = 0$

$C_5 = C_6 = 0$

Comparing of the Architectures

The transmitted impedance to the operator

$$Z_t = \frac{A + CZ_e}{B + DZ_e}$$

where

$$A \equiv (Z_m + C_m)(Z_s + C_s) + C_1 C_4$$

$$B \equiv (1 + C_6)(Z_s + C_s) - C_3 C_4$$

$$C \equiv (1 + C_5)(Z_m + C_m) + C_1 C_2$$

$$D \equiv (1 + C_5)(1 + C_6) - C_2 C_3$$

Position-Position Architecture

$$Z_t = \frac{(Z_m + C_m)(Z_s + C_s) - C_m C_s + (Z_m + C_m) Z_e}{(Z_s + C_s) + Z_e}$$

$$h = \begin{bmatrix} Z_m + C_m - \dfrac{C_m C_s}{Z_s + C_s} & \dfrac{C_m}{Z_s + C_s} \\ \dfrac{-C_s}{Z_s + C_s} & \dfrac{1}{Z_s + C_s} \end{bmatrix}$$

If C_m, C_s goes to infinite

$$h \Rightarrow \begin{bmatrix} Z_m + C_m - \dfrac{C_m C_s}{Z_s + C_s} & 1 \\ -1 & 0 \end{bmatrix}$$

Position-Force Architecture

$$Z_t = \frac{(Z_m + C_m)(Z_s + C_s) + (Z_m + C_m + C_s)Z_e}{(Z_s + C_s) + Z_e}$$

$$h = \begin{bmatrix} Z_m + C_m & 1 \\ \frac{-C_s}{Z_s + C_s} & \frac{1}{Z_s + C_s} \end{bmatrix}$$

if C_s goes to infinite $h \Rightarrow \begin{bmatrix} Z_m + C_m & 1 \\ -1 & 0 \end{bmatrix}$

If C_s goes to infinite and $C_m = -Z_m$ $h \Rightarrow \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$

Transparency optimized control law with four-channel

$$C_1 = (Z_s + C_s) \quad C_2 C_3 = 1$$

$$C_5 = C_6 = 0 \quad C_4 = -(Z_m + C_m)$$

$$\Rightarrow \quad Z_t = Z_e \qquad h = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$$

With local force feedback [H-Zaad, 1999]

$$C_1 = (Z_s + C_s) \qquad C_2 = 1 + C_6$$

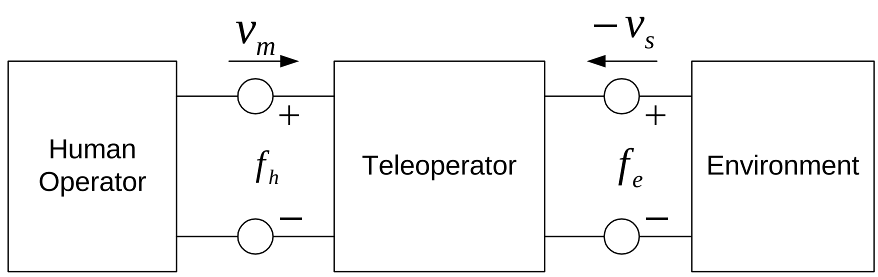
$$C_3 = 1 + C_5 \qquad C_4 = -(Z_m + C_m)$$

$$\Rightarrow \quad Z_t = Z_e \qquad h = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$$

Increase stability margin for the time delay teleoperation, because the feed-forward control gain C_2, C_3 can be attenuated by the local force feedback gain C_5, C_6

However, acceleration should be measured and the dynamic parameters of the master and slave should be known, perfectly.

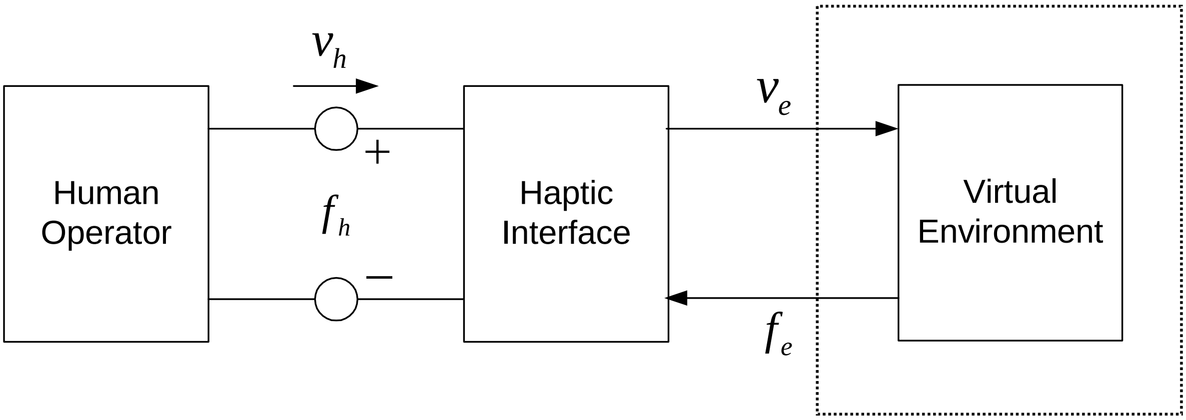
Network Model and Stability Condition



Teleoperator two-port should be passive

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

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

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

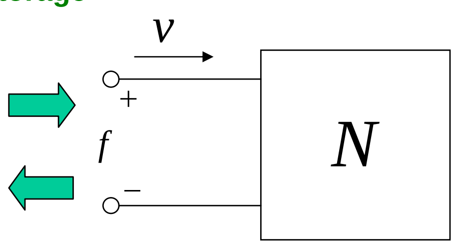
Net energy supplied **Initial energy storage**

f : Force

v : Velocity

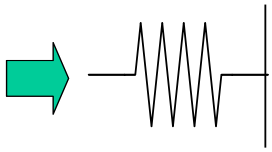
$f \cdot v > 0$

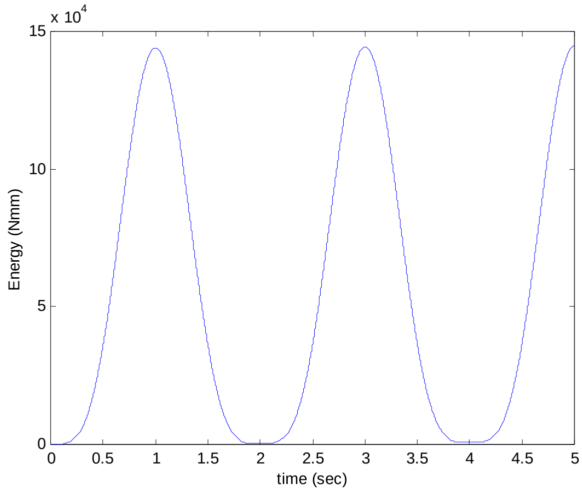
$f \cdot v < 0$



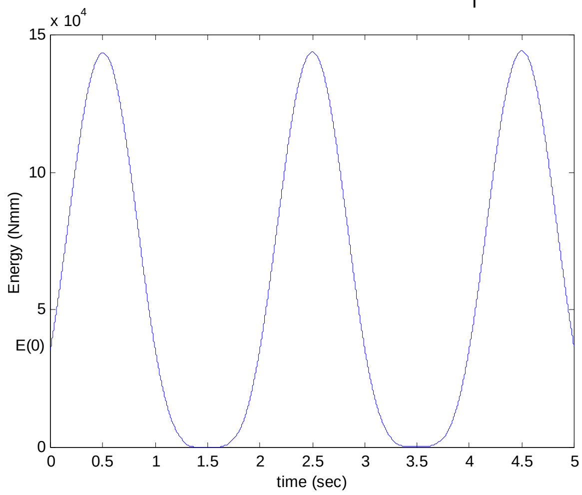
Energy Behavior of Spring

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



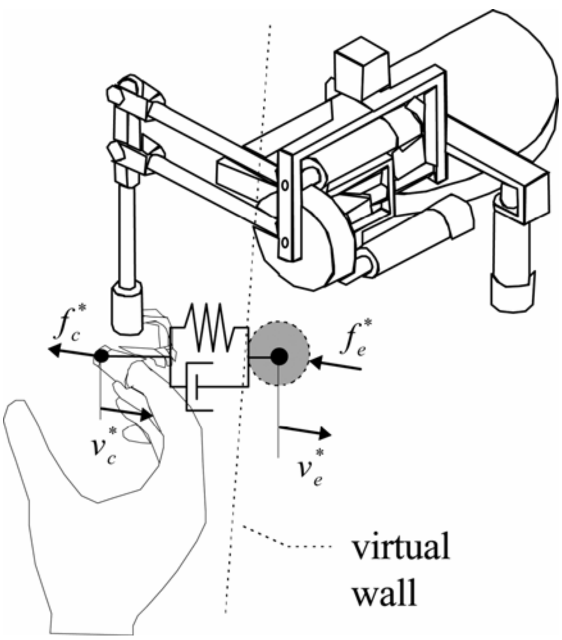


Zero initial condition



Initially deflected

Virtual Coupling



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

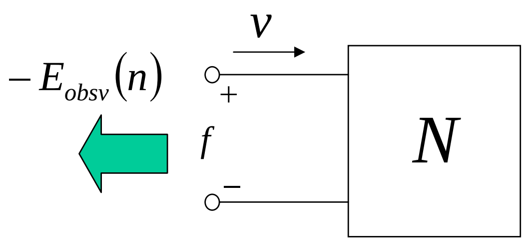
Passivity：

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

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

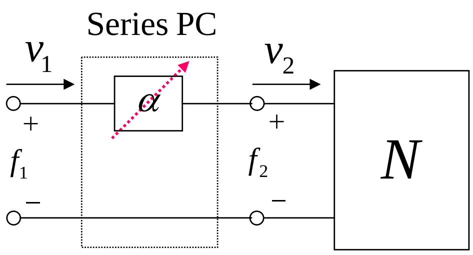
$E_{obsv}(n) \geq 0$: Passive

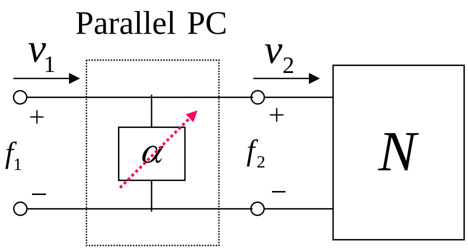
$E_{obsv}(n) < 0$: Active



-Hannaford and Ryu 2001-

Passivity Controller (PC) is an adaptive dissipation element





Series or velocity conserving — parallel or force conserving

Impedance causality — Admittance causality

-Hannaford and Ryu 2001-

Series PC Algorithm

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

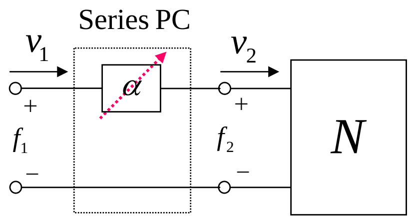
2) $f_2(n) = F_N(v_2(n))$

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

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

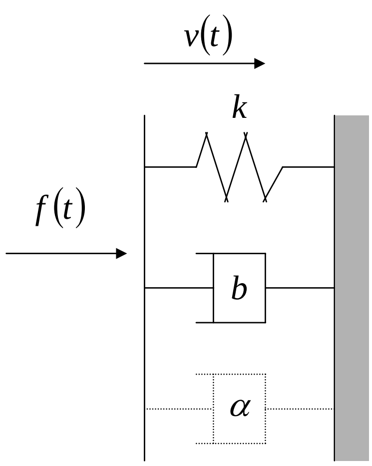
4) $$\alpha(n) = \begin{cases} -E_{obsv}(n)/\Delta T\ v_2(n)^2 & \text{if } E_{obsv}(n) < 0 \\ 0 & E_{obsv}(n) \geq 0 \end{cases}$$

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



-Hannaford and Ryu 2001-

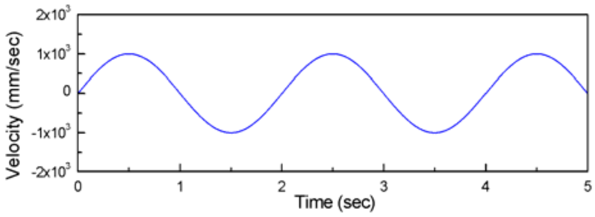
Simple Simulation with Impedance Type Virtual Wall



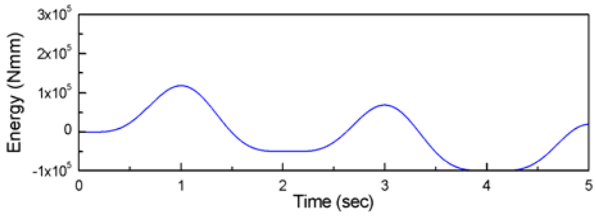
$k = 710\ N/m$

$b = 50\ Ns/m$

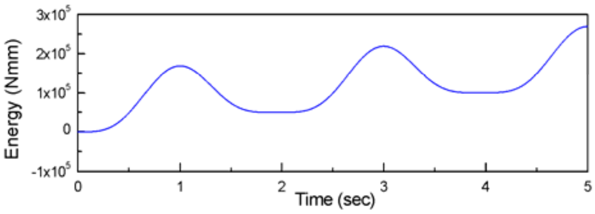
Simulation Results



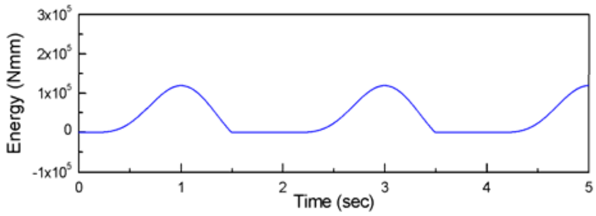
(a) Velocity Input



(c) Energy Generation

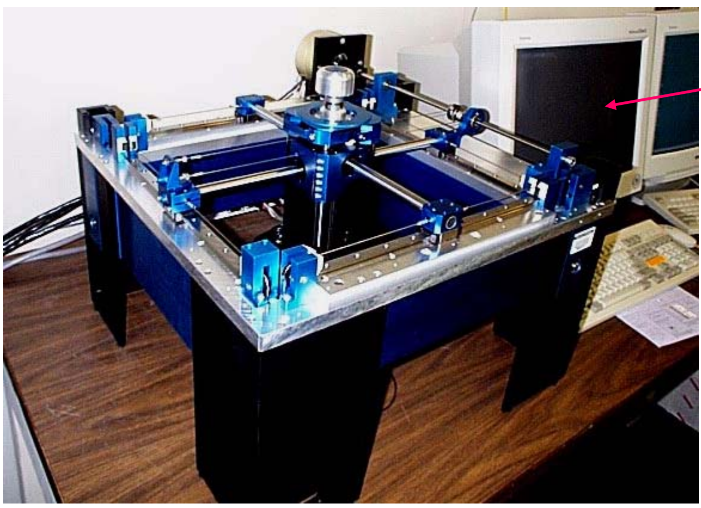


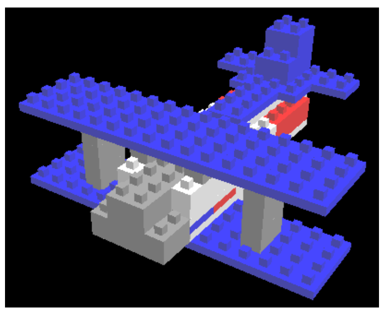
(b) Energy Dissipation



(d) Passivity Control

Excalibur Haptic Interface System





Haptic Experiment with the PC

Teleoperation Experiment with the PC