Control of Telerobotic Systems

Jee-Hwan Ryu

School of Mechanical Engineering
Korea University of Technology and Education
Unilateral vs. Bilateral

Master \rightarrow Slave

Master \leftrightarrow Slave
Unilateral Control
Bilateral Control

Master

Slave

Master

Slave
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
The hybrid two-port network model of teleoperator

Hybrid matrix

\[
\begin{bmatrix}
  f_m \\
  -v_s
\end{bmatrix} =
\begin{bmatrix}
  h_{11} & h_{12} \\
  h_{21} & h_{22}
\end{bmatrix}
\begin{bmatrix}
  v_m \\
  f_s
\end{bmatrix}
\]

\[h = \begin{bmatrix}
  \text{Input impedance} & \text{Force scale} \\
  \text{Velocity scale} & \text{output admittance}
\end{bmatrix}\]

\[h_{\text{ideal}} = \begin{bmatrix}
  0 & 1 \\
  -1 & 0
\end{bmatrix}\]
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.

\[
f_s = Z_e v_s \\
f_m = Z_t v_m
\]

Transparency condition

\[
Z_t = Z_e
\]
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 \[\leftrightarrow\] Impedance matching
Characteristics on Scaling

- **Micro**
  - Poor stability
  - Line of unity
    - Power gain
    - Line of unscaled impedance perception
  - eg. Micro surgery
  - Excellent stability
  - eg. Construction

- **Macro**

Mathematical equations:

\[ x_s = \lambda_p x_m \]
\[ f_s = \frac{1}{\lambda_f} f_m \]
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

Operator
\[ Z_h = m_{op} s + b_{op} + \frac{k_{op}}{s} \]

Master
\[ Z_m = m_m s + b_m \]
\[ C_s = C_1 = B_s + K_s / s \]
\[ C_m = -C_4 = B_m + K_m / s \]

Slave
\[ Z_s = m_s s + b_s \]

Environment
\[ Z_e = m_e s + b_e + \frac{k_e}{s} \]
Position/Force Architecture
Position/Force Architecture

\[ C_s = C_1 = B_s + \frac{K_s}{s} \]
\[ C_2 = 1 \]
\[ C_m = B_m \]
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

\[ Z_i = \frac{A + CZ_e}{B + DZ_e} \]

where

\[ A \equiv (Z_m + C_m)(Z_s + C_s) + C_1C_4 \]
\[ B \equiv (1 + C_6)(Z_s + C_s) - C_3C_4 \]
\[ C \equiv (1 + C_5)(Z_m + C_m) + C_1C_2 \]
\[ D \equiv (1 + C_5)(1 + C_6) - C_2C_3 \]
Position-Position Architecture

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

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

If \( C_m, C_s \) goes to infinite

\[ h \Rightarrow \begin{bmatrix} Z_m + C_m - \frac{C_m C_s}{Z_s + C_s} & 1 \\ -\frac{C_s}{Z_s + C_s} & 0 \end{bmatrix} \]
Position-Force Architecture

\[ Z_t = \frac{(Z_m + \mathcal{C}_m)(Z_s + \mathcal{C}_s) + (Z_m + \mathcal{C}_m + \mathcal{C}_s)Z_e}{(Z_s + \mathcal{C}_s) + Z_e} \]

\[ h = \begin{bmatrix} Z_m + \mathcal{C}_m & 1 \\ -\mathcal{C}_s & 1 \\ Z_s + \mathcal{C}_s & Z_s + \mathcal{C}_s \end{bmatrix} \]

if \( \mathcal{C}_s \) goes to infinite \( h \Rightarrow \begin{bmatrix} Z_m + \mathcal{C}_m & 1 \\ -1 & 0 \end{bmatrix} \)

If \( \mathcal{C}_s \) goes to infinite and \( \mathcal{C}_m = -Z_m \) \( h \Rightarrow \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \)
Transparency optimized control law with four-channel

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

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

\[ \Rightarrow Z_t = Z_e \quad h = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \]
With local force feedback [H-Zaad, 1999]

\[ C_1 = (Z_s + C_s) \quad C_2 = 1 + C_6 \]
\[ C_3 = 1 + C_5 \quad C_4 = -(Z_m + C_m) \]
\[ \Rightarrow Z_t = Z_e \quad h = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \]

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.
Teleoperator two-port should be passive

$$\int_0^t (f_h(\tau)v_m(\tau) - f_e(\tau)v_s(\tau)) d\tau \geq 0, \quad \forall t \geq 0$$
Virtual Environment one-port should be passive

\[ \int_0^t f_e(\tau)v_e(\tau)d\tau \geq 0, \quad \forall t \geq 0 \]
Passivity

- Principle of conservation of energy:
  - “Energy supplied BY the network can never exceed the energy which has been fed TO it”

- Mathematical definitions

\[
\int_0^t f(\tau)v(\tau)\,d\tau + E(0) \geq 0, \quad \forall t \geq 0
\]

Net energy supplied Initial energy storage

\( f \): Force \quad \quad f \cdot v > 0

\( v \): Velocity \quad \quad f \cdot v < 0

\( N \)
Energy Behavior of Spring

\[ \int_0^t f(\tau)v(\tau)d\tau + E(0) \geq 0, \quad \forall t \geq 0 \]

Zero initial condition  Initially deflected
Virtual Coupling
Passivity Observer (PO) can measure energy flow in real-time

Passivity:
\[ \int_0^t f(\tau)v(\tau) \, d\tau \geq 0, \quad \forall t \geq 0 \]

PO:
\[ E_{\text{obs}}(n) = \Delta T \sum_{k=0}^{n} f(k)v(k) \]

- \[ E_{\text{obs}}(n) \geq 0 : \text{Passive} \]
- \[ E_{\text{obs}}(n) < 0 : \text{Active} \]

-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 \( F_N(\cdot) \) is the output of the one-port

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

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

5) \( f_1(n) = f_2(n) + \alpha(n) v_2(n) \Rightarrow \text{output} \)

-Hannaford and Ryu 2001-
Simple Simulation with Impedance Type Virtual Wall

\[ k = 710 \text{ N/m} \]
\[ b = 50 \text{ Ns/m} \]
Simulation Results

(a) Velocity Input

(b) Energy Dissipation

(c) Energy Generation

(d) Passivity Control
Excalibur Haptic Interface System
Haptic Experiment with the PC
Teleoperation Experiment with the PC