Time Domain Passivity Control of Haptic Interfaces with Virtual Environments

1. Stability Condition
2. Time Domain Passivity Approach
3. Experimental Results
Haptic Interaction System Overview

3D Graphics Processor

Virtual Environment or Model

Mechanism

Haptics Processor

Power Converter

60Hz

1000 Hz
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**

  \[
  N \geq 0, \quad \forall t \geq 0
  \]

  \[
  f(v) \cdot v \geq 0
  \]

  \[
  -f(v) \cdot v < 0
  \]

  \[
  f : \text{Force} \quad \quad \quad f \cdot v > 0
  \]

  \[
  v : \text{Velocity} \quad \quad \quad f \cdot v < 0
  \]
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
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) \( E_{obsv}(n) = E_{obsv}(n-1) + [f_2(n)v_2(n) + \alpha(n-1)v_2(n-1)^2]\Delta T \)

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

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
Experimental Video Clip
Contact with High Stiffness without PC ($k = 90 \text{ kN/m}$)

- 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

- 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

$$\int_0^t (f_h(\tau)v_m(\tau) + f_e(\tau)v_s(\tau))d\tau \geq 0, \quad \forall t \geq 0$$
Passivity Observer for 2-port network is similar

\[ E_{\text{obsv}}(n) = \Delta T \sum_{k=0}^{n} (f_1(k)v_1(k) + f_2(k)v_2(k)) + E(0) \]

\[ = \Delta T \cdot W(n) \]
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

\[ N \]

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

\[ E_{\text{obs}v}(n) = \Delta T \sum_{k=0}^{n} (f_m(k)v_m(k) + f_s(k)v_s(k)) = \Delta T \cdot W(n) \]
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

- Stable contact can be achieved even the Environment has high stiff
Hard Contact with High Velocity and without PC

- Contact is unstable
- PO<0
Hard Contact with High Velocity and with PC

- 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

- Contact become unstable during the following
- PC become negative
Following the Slanted Hard Wall with PC

- Following is stable
- PC output consists of noise-like signal during low velocity
Contact with Soft Sponge with High Velocity without PC

- 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
Physical Analogy of Motion Control Systems

\[ \text{Trajectory generator} \quad \begin{array}{c} v_d \\ \tau \end{array} \quad \text{Controller} \quad \text{Plant} \]

\[ \begin{array}{c} v \\ F_{\text{friction}} \end{array} \]
Network Model of Motion Control Systems

![Diagram of network model](image)

- **Virtual energy flow**
  - Trajectory Generator
  - Controller
  - Plant
  - Input energy

- **Physical energy flow**
  - Output energy

**Tracking controller**

- $v_d$
- $\tau$
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

• Input energy depend on connected network

• Connected network is passive \(\rightarrow\) marginally passive

• Plant is uncertain zero \(\sim\) 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

\[ E_{\text{obs}v}(n) = \Delta T \sum_{k=0}^{n} (\tau(k)v_d(k) - \tau(k)v(k)) + E(0) = \Delta T \cdot W(n) \]

\[ v_d = 0 \]
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

- Regulation is unstable
Nominal LQ Regulator with PC

- Stable regulation is achieved
- During the rise time, PC is only activated several times ($E(0)=0.055$)
Polytopic Robust LQ regulator

- 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

![Graph showing comparison of PC Approach with Nominal LQ Controller w/o Perturbation](image)

- **Tip Position (m)**
  - Perturbed system w/ nominal LQ and PC
  - Nominal system w/ nominal LQ w/o PC
  - & Nominal system w/ nominal LQ and PC

- **Torque (Nm)**

![Graph showing torque over time](image)
Nominal LQ Regulator when Quantization effect is added

- 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.
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

- Control is unstable
- PO < 0
Tip-position PD Control with PC

- Stable tracking is achieved
- PC is activated only if required