Control for Haptic Rendering
Workshop zu interaktiven VR-Technologien für On-Orbit Servicing

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Motivation

Why haptic rendering?

haptic rendering = computation and display of forces from the VR

assembly simulation  training
Introduction

**Visual rendering** 30Hz

**Display**

**Input device**

**Human**

**Visual modality**

**Haptic modality**

**Models**

**Data**

**Object pose**

**Visual signals**

**Haptic signals**

**Haptic device**

Data

**Haptic rendering** 1kHz

**Force**

**Pose** movements

**Visual signals**

**Data**
Introduction

data → visual rendering (30Hz) → display (visual signals)

models → object pose → e.g. camera position → visual modality

haptic rendering (1kHz) → haptic device (haptic signals) → movements

forces → pose → human (haptic modality)
Introduction

Visual rendering → 30Hz → Display

Visual signals → Human

Haptic signals → Haptic device

Data → Object pose → Human

Goal: Maximal immersion

Data → Haptic rendering → 1kHz → Haptic device

Human → Movements → Haptic signals

Models

Data → Visual signals → Visual signals
Requirements for haptic devices

- 6 DoF passive and active (feedback of forces and torques)
- Large workspace
- Low inertia
- Large maximal forces & high dynamic
- High sampling rate (rule of thumb: at least 1kHz)
- Small delays
- High structural stiffness

Additionally: Safety aspect
Light Weight Robot

Properties:
- 7 DoF
- Torque sensor in each joint  \(\rightarrow\) impedance control
- Workspace comparable to that of a human arm
- Low weight (~15 kg)
- Fast sampling
  1kHz: Cartesian
  3kHz: inside joints
- Safety concept (redundant sensors, safety breaks, deadman loop, …)

well suited as haptic device

LBR1 (1991)  
LBR2 (1998)  
LBR3 (2001)  
KUKA LBR (2006)
Bimanual Haptic Device
Fields of Application

Telepresence

Virtual Assembly / Training

Requirements

Haptic simulations must be
- safe
- intuitive
- performant (transparent)
Fields of Application

Field: Telepresence

How can we meet these requirements by haptic control?

- safe
- intuitive
- performant (transparent)
Feed-Forward Control

**Motivation**: Reduce effective inertia ➔ improve intuitive usage

\[ F_{\text{fwd}} = \frac{Z_m}{1+k} \]

**Total impedance**

\[ Z_{\text{total}} = \frac{X}{F} = \frac{Z_m}{1+k} \]

Effective reduction for the LWR: ca. 66%
Null Space Optimization

**Motivation**: Avoid singularities & maximize distance to human operator

Different criteria:
- Maximize distance to user
- Optimize configuration (joint limits, singularities)
  ➔ Compliant behavior
Collision Avoidance

**Motivation**: Requirement for safe operation

- Collisions between robots & table
- Collisions between the two robots

For both:
- Tool and each link are checked
- Spring-damper model
Stable Interaction

**Motivation**: Requirement for safe operation

- Collisions between virtual objects
- Spring-damper model
Stable Interaction
Virtual springs are active!
Stable Interaction
Virtual springs are active!
Stable Interaction

Virtual springs are active!

\[ F \]

energy gain \( E_G \)

spring \( K \)

\[ x_{wall} \]

\[ x \]
Stable Interaction
Virtual springs are active!

\[ F \]

\[ k \]

energy gain \( E_G \)

\[ x_{\text{wall}} \]

\[ x \]

delay

delay

\[ K \]

\[ B \]
Stable Interaction
Virtual springs are active!

For which $B$ is the haptic system stable?
Assumptions

- 1 DoF
- Linear model of human
- No nonlinear effects
- Delay is permitted
- Direct coupling between $m_L$ and $m_H$

Virtual Wall

$K$: virtual stiffness
$B$: virtual damping

Haptic Device

$b_L$: physical damping
$m_L$: mass

Human

$k_H$: physical stiffness
$b_H$: physical damping
$m_H$: mass
**System Description**

**Assumptions**

\[ m = m_L + m_H \]
\[ b = b_L + b_H \]
\[ k = k_H \]

**Virtual Wall**
- \( K \): virtual stiffness
- \( B \): virtual damping

**Haptic Device**
- \( b_L \): physical damping
- \( m_L \): mass

**Human**
- \( k_H \): physical stiffness
- \( b_H \): physical damping
- \( m_H \): mass
System Description
Assumptions

\[ K : \text{virtual stiffness} \]
\[ B : \text{virtual damping} \]
\[ k : \text{physical stiffness} \]
\[ b : \text{physical damping} \]
\[ m : \text{mass} \]
System Description
Control Loop

Consists of continuous- and discrete-time blocks

- Use ZOH-Equivalent of continuous-time block
  ( = Exact description! )
System Description

Control Loop

\[ \mathcal{F}(z, T, m, k, b) = \frac{(c_2 + c_3 - 2) z + (c_2 + c_3 - 2 e^{-bT/m})(b^2 - 4km) + bc_1 (c_3 - c_2) (z - 1)}{2k(z^2 - (c_2 + c_3)z + e^{-bT/m})(4km - b^2)} \]

with

\[ c_1 = \sqrt{\frac{(bT/m)^2 - 4kT^2}{m}} \]
\[ c_2 = e^{-\left(bT/m + c_1\right)/2} \]
\[ c_3 = e^{-\left(bT/m - c_1\right)/2} \]
System Description
Normalization

\[ \alpha = \frac{K \cdot T^2}{m} : \text{normalized virtual stiffness} \]
\[ \beta = \frac{B \cdot T}{m} : \text{normalized virtual damping} \]
\[ \gamma = \frac{k \cdot T^2}{m} : \text{normalized physical stiffness} \]
\[ \delta = \frac{b \cdot T}{m} : \text{normalized physical damping} \]

Characteristic Equation

\[ 0 = \left( (c_3 + c_2 - 2)c_1 + (c_3 - c_2)\delta \right) (\alpha + \beta) z^2 \]
\[ + \left( \left( (c_3 + c_2 - 2e^{-\delta})c_1 + (c_2 - c_3)\delta \right) \alpha \right) z \]
\[ + 2 \left( \left( 1 - e^{-\delta} \right) c_1 + (c_2 - c_3)\delta \beta \right) z \]
\[ - 2 \left( z^2 - z(c_3 + c_2) + e^{-\delta} c_1 \gamma z^{1+d} \right) \]
\[ + \left( (2e^{-\delta} - c_3 - c_2)c_1 + (c_3 - c_2)\delta \beta \right) \]

\[ \text{with } c_1 = \sqrt{\delta^2 - 4\gamma} \]
\[ c_2 = e^{-(\delta + c_1)/2} \]
\[ c_3 = e^{-(\delta - c_1)/2} \]

▷ Mass \( m \) and Sampling Period \( T \) dropped out!
Normalized Stability Boundaries

Simple case: \( \gamma = \delta = 0 \)

\[
\begin{align*}
\alpha &= K \cdot T^2 / m \\
\beta &= B \cdot T / m \\
\gamma &= k \cdot T^2 / m \\
\delta &= b \cdot T / m \\
d &= T_d / T
\end{align*}
\]
Normalized Stability Boundaries

\[ \gamma = \delta = 0 \]

\[
\begin{align*}
\alpha &= \frac{K \cdot T^2}{m} \\
\beta &= \frac{B \cdot T}{m} \\
\gamma &= \frac{k \cdot T^2}{m} \\
\delta &= \frac{b \cdot T}{m} \\
d &= \frac{T_d}{T}
\end{align*}
\]
Normalized Stability Boundaries

\[ \gamma = \delta = 0 \]

\[
\alpha = \frac{K \cdot T^2}{m} \\
\beta = \frac{B \cdot T}{m} \\
\gamma = \frac{k \cdot T^2}{m} \\
\delta = \frac{b \cdot T}{m} \\
d = \frac{T_d}{T}
\]
Parameter Range

for haptic devices holds

\[
\frac{b_L}{m_L} < 0.625 \text{s}^{-1} \quad \frac{T}{T} \leq 0.001 \text{s}
\]


for human arms holds

\[
0 \leq \frac{k_H}{m_H} < 710 \text{s}^{-2} \quad 0 \leq \frac{b_H}{m_H} < 12.6 \text{s}^{-1}
\]


\[
0 \leq \gamma < 1 \cdot 10^{-3} \quad 0 \leq \delta < 15 \cdot 10^{-3}
\]
Normalized Stability Boundaries

$$\gamma = [0, 0.001], \ \delta = [0, 0.015], \ d = 0$$

$$\alpha = K \cdot \frac{T^2}{m}$$
$$\beta = B \cdot \frac{T}{m}$$
$$\gamma = k \cdot \frac{T^2}{m}$$
$$\delta = b \cdot \frac{T}{m}$$
$$d = \frac{T_d}{T}$$
Experiments
Conclusions

- The DLR Bimanual Haptic Device
  Light Weight Robots
  Applications

- Control Aspects
  Feed-Forward Control
  Null Space Optimization
  Collision Avoidance
  Virtual Contacts

- Stability Analysis
  Stability Boundaries
Thank you for your attention!