Haptics for Immersive and Dynamic Virtual Worlds

Presenter

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Tutorial description

A introduction to virtual worlds with haptic sensation: its history, techniques, and recent advances, with a particular emphasis on string-based haptic interface SPIDAR. The first half of the course is a basic introduction to haptic devices and immersive virtual environment with haptic sensation. The second half covers several advanced techniques, including haptic rendering techniques, physically-based dynamic simulation for haptic interaction, and reactive virtual human. The real-time demonstrations using SPIDAR-system are programmed.

Contents

9:00-9:30 Introduction -- Sato
1. Overview of haptic interaction
2. String-based haptic device :SPIDAR

9:30-10:15 Immersive and Interactive virtual environments - Jeong
3. Immersive Virtual Environment (VE)
4. Interactive VE : Reactive Virtual Human

10:15-10:30 Break Time

10:30-11:15 Haptics in dynamic virtual worlds -- Hasegawa
5. Haptic interaction by SPIDAR
6. Real-time Rigid Body Simulation for Haptic Interactions

11:15-12:00 Demonstration and Discussion
7. Demo using SPIDAR system
8. Discussion
**What is SPIDAR?**

"SPIDAR" is not "SPIDER"

**OUTLINE**

Virtual World of:
- Watch and Touch
- Pick and Place
- Peg in Hole
- Hand in Hand
- Open a Door
- Grasp and Move
- 4 + 4 Fingers

**Watch and Touch**

SPIDAR-I
指先に対して4本の糸が張られている
ロータリーエンコーダで
糸の長さを計測して
指先の3次元位置を計算する
モーターで糸の張力を制御して
指先に任意の力を加える

SPIDAR - I

SPIDAR - II

BOTH HANDS SPIDAR

Both hands manipulation

Pick and Place

Peg in Hole
Hand in Hand

NETWORKED SPIDAR

Human-Scale Interaction

SPIDAR-H

SIGGRAPH97
Grasp and Move

- Grasp object
- (6 + 1) DOF manipulation

SPIDAR-G

三次元グリップ

トレンドたまご

Both-handed SPIDAR-G
Multi-fingers Task

SPIDAR-8

Virtual Rubik Cube

SIGGRAPH2000

Summary

- SPIDAR I
- SPIDAR II
- BOTH HANDS SPIDAR
- NETWORKED SPIDAR
- BIG SPIDAR
- SPIDAR-G
- SPIDAR-8

No of Strings
Summary

Features of SPIDAR
- Tension-based
- Finger-based systems
- Ground-referenced Force Feedback
- > 3DOF
- General Purpose

Why string?
- simple
- smooth
- safe
**Terminology**

- **Virtual Reality** refers to “Immersive Virtual Reality”
  - "Virtual Reality is the use of computer technology to create the effect of an interactive three-dimensional world in which the objects have a sense of spatial presence.”

- **Immersion**: “the extent to which computer displays are capable of delivering an inclusive, extensive, surrounding, and vivid illusion of reality to the senses of the VE participant.” (Slater and Wilbur, ’97)

**Presence?**

- **Presence**: is defined as “being there,” and those are involvement and immersion
- **Social presence**: feeling that one is present with another person at a remote location
- **Virtual presence**: feeling as if present in a remote environment

Factors which affect immersion include isolation from the physical environment, perception of self-inclusion in the virtual environment, natural modes of interaction and control, and perception of self-movement. (Witmer and Singer 1998, presence)

**Types of VR System**

- **Non-immersive (desktop)**
- **Semi-immersive**: Embedded without personal presentation equipment (ImmersaDesk, CAVE™, a table-size stereo display with head tracking)
- **Fully immersive**: Embedded inside the environment (CAVE, CYBERSPHERE...)

**Performance of VR systems**

- **Qualitative performance of different VR systems (Kalawsky, 1996)**

<table>
<thead>
<tr>
<th>Main Features</th>
<th>Non- Immersive VR (Desktop)</th>
<th>Semi-Immersive VR (Projection)</th>
<th>Full Immersive VR (Head-coupled)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>High</td>
<td>High</td>
<td>Low - Medium</td>
</tr>
<tr>
<td>Scale (perception)</td>
<td>Low</td>
<td>Medium - High</td>
<td>High</td>
</tr>
<tr>
<td>Navigation skills</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Field of regard</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Lag</td>
<td>Low</td>
<td>Low</td>
<td>Medium - High</td>
</tr>
<tr>
<td>Sense of immersion</td>
<td>None - low</td>
<td>Medium - High</td>
<td>Medium - High</td>
</tr>
</tbody>
</table>

**Immersive Projection System(1)**

<table>
<thead>
<tr>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample shape of screen to project</td>
<td>Some distortion problems at the orthogonal joint area by screens</td>
</tr>
<tr>
<td>High Performance is possible</td>
<td></td>
</tr>
</tbody>
</table>
### D-vision (Multi-Projection System)

- **Advantage**
  - Duplex Vision: central view + peripheral view (2 FOV)
  - Division: divided to 16 areas
  - 4,500 x 3,500 pixel images by 24 PCs and 24 Projectors
  - 180 degrees of view angle
  - Screen size: 6.3m x 4.0m x 1.5m
  - Stereoscopic image by linear polarized light

- **Disadvantage**
  - Hard to focus the image on the curved screen because of the characteristic of its shape

### Feature of D-vision (1)

- Direction of Projection
  - **Front Projection**
    - Peripheral View (Right and Left, Ceiling, Floor)
  - **Rear Projection**
    - Central View (Center - 4 area)

### Feature of D-vision (2)

- **Screen Shape**
  - Whole Curved Screen
  - Curved + Plane

### Feature of D-vision (3)

- **Flexible Integration:**
  - Human-scale Haptic and Locomotion Interface, Cameras
  - Transparent
  - Opaque

- **Space for haptic interface installation**
**The position of Projectors**

(Left Side)

(Plan) Rear Projectors

Front Projectors

2.7m 2.2m

4.0m

**Projection method**

Axis of the projection

Texture mapping to the virtual sphere surface

Photos by fish eye lens

Center of lens

Screen

User

Fish-eye lens Surface

**Projector Installation**

Behind of Screen

Front of Screen

Array image of Front Projectors

**Distributed Rendering with PC Cluster**

Computer hardware of PC cluster

New Spec.

- **OS**: WindowsXP or Linux
- **CPU**: Dual Pentium III 800Mhz : (Pentium IV 2Ghz)
- **Memory**: 512 MB
- **Graphic Card**: NVIDIA GeForce 2 Ultra : (GeForce 4 Ti 4600)
- **Network**: 100Mbps Ethernet card
  + Myrinet [released by Myricom ]
  + full-duplex 2+2 Gbit/s data rate

**Image Processing Hardware**

Multi-Projection for Different Shaped
Hard to render image real-time

Geometric Correction

Edge Blending

Model PA99

Model PA21

**Image-Based Rendering**

Real Photo Image

To experience virtual space

High-resolution

High-immersive

Easiest way to make virtual space contents
**Generation of Seamless Images**

- **Stereoscopic Area**
- 16 Images for 24 PCs
- Projected Images on Screen
- 24 PCs → Geometry Correction → Edge Blending → Real-time Image processor → Projector

**Seamless Image Generation Method**

- **Existing...**
  - Seamless Method from assumed one view
- **Proposal...**
  - Seamless Method for corresponding any view

**Edge Blending**

- Overlapped projection → Computed edge blending pattern
- The relative positional relationship of pixels

**Locomotion Interface - Turntable**

- Explore the virtual space freely with his natural stepping on the device
- Always face the front of the Screen
- No need to wear any gear

**Turntable Demo**

**Human-scale Haptic Interface**

- **SPIDAR-H (Space Interface Device for Artificial Reality in Human Scale)**
  - Human-scale
  - Wire-driven
  - Freedom of Movement
  - Smooth & Safe

<table>
<thead>
<tr>
<th>Accuracy</th>
<th>ε ≤ 1.2cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Force</td>
<td>Max. 30N</td>
</tr>
</tbody>
</table>
SPIDAR-H DEMO

Applications

Design plan & Architectural Design

Education & Entertainment

Dynamic and Interactive VE and Reactive Virtual Human

Applications


User Interfaces

The VR Process (siggraph 04, Course)

• Begins with user inputs to the User Interface
• Alter the internals of the virtual world
• Represent the VE
• User-centric rendering
• Display to the user
**Interactive VE(1) – Control**

Animating Athletic Motion Planning By Example (Graphics Interface 2000)

Sympathetic interfaces: Using a plush toy to direct synthetic characters (CHI 1999)

Anyone for tennis? (wearing mocap)

Students Engaged in Virtual 'Field' Work (SIGGRAPH 2003)

**Interactive VE(2) - Vision+Audio**

With the Virtual Football Trainer, you can move to any position on the field to experience the game from the player's perspective (Univ. of Michigan, 2003)

Humanoid Agent: Gesture and Narrative language Recognition (MIT, 2001)

**Sensory System**

- Audio Only
  - not good enough for full interaction
- Vision & Audio
  - comfort level but still ambiguous when interacting about specifics
- Virtual Reality environments allow people to communicate through multi-modal pathways
  - Social-presence
    - allows higher degree of interaction with others
  - Direct & Intuitive operation is possible

**Dynamic & Intuitive Interaction?**

- Accompany *Reactive motion* in the interaction that involves taking action in our daily life
  - Ex) a handshake, hug, dance, sports..
- *Interaction with Force Feedback* is an important communication!
- We address it “responsive motion” which occurred by the force input from outside

**Reactive Virtual Human**

Realize *Reactive Virtual human* which is capable of *Force interaction* with user

- Behavioral realism
- Better active communication
- Intuitive and direct interaction with user

It will be new potential in other interaction system and human factor analysis, training task, entertainment applications, etc.

**Basic Concept of Reactive VH**
System Organization

Implemented System

Motion generation

- Motion of Virtual Human
  - Dynamic simulation
  - Motion Capture
  - Combining motion capture and simulation

Reactive Motion Generation

- Adopted motion capture system for constructing database of real movements
- Reactive Motion generation from motion database and Haptic interface
  - Real-time motion by physical parameter
  - Rich expression by motion data
  - Best-fit motion according to user’s action

Reactive Virtual Human

"Virtual Catch Ball"
Future Works

- Problems to be solved
  - Reinforce a grasping sensibility (interface)
  - Smoother motion generation of virtual human
  - Require better immediacy and intuitiveness of integrated system
- Challenges
  - Integrate other senses (tactile, gaze, hearing...)
  - Adopt combination method of Database and Kinematics

Summary

- Described a multi-modal interaction system & applications in an immersive VE
- Introduced "Reactive Virtual Human"
  - Realized force feedback with user in human-scale virtual environment
  - Generated Reactive Motion based on haptic Information from abundant motion data
Haptic interaction by SPIDAR

Shoichi Hasegawa
Makoto Sato’s group
Precision and Intelligence Lab.
Tokyo Institute of Technology

Hardware of SPIDAR

Motor and encoder
Present force to user.
Measure length of string.

Hardware performance

SPIDAR is the best device in performance
Stiff and light

<table>
<thead>
<tr>
<th></th>
<th>SPIDAR</th>
<th>PHANTOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape</td>
<td><img src="shape.png" alt="Image" /></td>
<td><img src="phantom.png" alt="Image" /></td>
</tr>
<tr>
<td>Stiffness</td>
<td>20 N/mm</td>
<td>20 N/mm</td>
</tr>
<tr>
<td>Weight</td>
<td>50g</td>
<td>75g</td>
</tr>
</tbody>
</table>

Position measurement

\[ l_i^2 = \| p_i - q_i \|^2 \]
\[ p_i = g_i(r) \]

Reconfigurable hardware

Any DOF and arrangements are designable.

Same control algorithm can be used

<table>
<thead>
<tr>
<th>DOF</th>
<th>Strings</th>
</tr>
</thead>
<tbody>
<tr>
<td>3DOF</td>
<td>4Strings</td>
</tr>
<tr>
<td>7DOF</td>
<td>8Strings</td>
</tr>
<tr>
<td>6DOF</td>
<td>8Strings</td>
</tr>
</tbody>
</table>

Contact simulation

- Contact force modeling
- Haptic rendering for 6DOF
- Simulation of articulated body
Position measurement

\[
\begin{aligned}
\mathbf{t}^* &= \mathbf{p}_i - \mathbf{q}_i \quad \rightarrow \quad \mathbf{p}_i = g(r) \\
\mathbf{t} &= \mathbf{p}_i - g(r)
\end{aligned}
\]

\[\left[ \begin{array}{c}
\frac{\partial g}{\partial p_x} \\
\frac{\partial g}{\partial p_y} \\
\frac{\partial g}{\partial p_z} \\
\frac{\partial g}{\partial r_x} \\
\frac{\partial g}{\partial r_y} \\
\frac{\partial g}{\partial r_z}
\end{array} \right] \Delta \mathbf{p} = \begin{array}{c}
\frac{\partial g}{\partial p_x} \\
\frac{\partial g}{\partial p_y} \\
\frac{\partial g}{\partial p_z} \\
\frac{\partial g}{\partial r_x} \\
\frac{\partial g}{\partial r_y} \\
\frac{\partial g}{\partial r_z}
\end{array} \Delta \mathbf{r}
\]

\[\Delta \mathbf{l} = J^T_p \mathbf{f} \quad \rightarrow \quad \text{Solve } \mathbf{r} \text{ by iterative method}
\]

Displaying force

- **Simple solution**
  \[\mathbf{f} = \begin{array}{c}
\phi_1 \\
\cdots \\
\phi_i \\
\cdots \\
\phi_j \\
\cdots \\
\phi_m
\end{array} \]
  \[\mathbf{r} = \begin{array}{c}
r_1 \\
\cdots \\
r_i \\
\cdots \\
r_j \\
\cdots \\
r_m
\end{array} \]

- **Discontinuous problem**
  Full presentation area
  Partial presentation area

- **Use smaller tension**
  \[\sum_{i=1}^{m} \tau_i^2 \rightarrow 0\]

- **Limitation**
  \[\tau_{\min} \leq \tau_i, \tau_j \leq \tau_{\max}\]

- **Finally**
  \[\sum_{i=1}^{m} \tau_i \phi_i - \mathbf{f} + \lambda \sum_{i=1}^{m} \tau_i^2 \rightarrow 0 \quad (\tau_{\min} \leq \tau_i, \tau_j \leq \tau_{\max})\]

  Quadratic programming problem

- **Expanded figure**

- **Calculated tension [N]**
  Full presentation area
  Partial presentation area

- **x component of presentation force [N]**
  Expanded figure

- **x coordinate of end effector [m]**

- **Finally**
  \[\sum_{i=1}^{m} \tau_i \phi_i - \mathbf{f} + \lambda \sum_{i=1}^{m} \tau_i^2 \rightarrow 0 \quad (\tau_{\min} \leq \tau_i, \tau_j \leq \tau_{\max})\]

  Quadratic programming problem

- **Expanded figure**
1. Measure finger position
2. Collision detection and force calculation
3. Display the force

Virtual World

F=kx

Finger position

Out of the object

In the object

Stable contact

F=kx

Stiff objects (large k) make too much force

Problem on slow update rate

Solution by fast update rate

Stiff object requires fast update.
It is commonly said that 1kHz or more is needed.

Advantage of stiffness

Display of friction disturbs display of shapes.
But, enough stiffness realizes both.

Effect of fast update

Trajectory of the haptic pointer on surfaces with friction (µ=0.5)

Real-time Rigid Body Simulation for Haptic Interactions

Touch the virtual world
User feels contact force from haptic interface
Haptic interaction

- Touch the virtual world
  - User feels contact force from haptic interface

- The touched object receives force from the user.
- The response: Dynamics

Contact force

\[ \mathbf{F}_c = m \ddot{\mathbf{v}} \]

\[ \mathbf{N} \mathbf{I} \cdot \mathbf{I} + \mathbf{M} = \mathbf{v}(t+\Delta t) - \mathbf{v}(t) + \mathbf{F}/m \Delta t \]

\[ \omega(t+\Delta t) - \omega(t) = \mathbf{I}^{-1} \mathbf{N} \Delta t \]

Contact model

- Normal force
  - Prevent penetration

- Friction force (Coulomb’s model)
  - Static friction
    - Prevent sliding motion
  - Dynamic friction
    - Proportional to normal force

Contact model

- Normal force
  - Friction force

Solving constraints (1)

- Analytical method
  - David Baraff SIGGRAPH ’89 ...

\[ \mathbf{M} \dot{\mathbf{r}} = \mathbf{f} \quad (\text{eq. of motion}) \]

\[ (\mathbf{p} - \mathbf{p}_j) \cdot \mathbf{n}_j \geq 0 \quad (\text{normal}) \]

\[ \mathbf{f} \cdot \mathbf{n} / |\mathbf{f}| \geq \mu \sqrt{1 + \mu^2} \quad (\text{friction}) \]

Advantages
- Object motions are stable.
- Wide time steps are affordable.
- Solves constraints accurately.
- Completely rigid.

Drawbacks
- Much computation time for one step. \( O(n^3) \)
- A virtual coupling is needed to connect a haptic interface.
- Coulomb’s friction model comes to NP complete problem.

Solving constraints (2)

- Penalty method

\[ \mathbf{f}_p = k \mathbf{d} + \lambda \mathbf{d} \quad \text{Spring Damper} \]

\[ \mathbf{f}_s = k_s \mathbf{v} \quad \text{Spring Damper} \]

Advantages
- Very fast for one step. \( O(n) \)
- Direct connection to haptic interfaces.
- Coulomb’s friction model is easily realized.
- Integration of other models are easy.
  - (e.g. Featherstone’s method)

Drawbacks
- Stability and rigidity requires small time steps.
- Treatment of large contact area makes instability or takes a lot of computation time.
Problem on large contact area

Where should we put spring-damper model?

- On the most penetrating point

Problem on large contact area

Where should we put spring-damper model?

- On vertices

Problem on large contact area

Where should we put spring-damper model?

- Many points

Proposal for the problem

Integrate forces from distributed model for each triangle.

Steps

Finding Contact force:
1. Find contact point and normal.
2. Find the shape of the contact volume.
3. Integrate forces over the contact area.

Contact detection

Gilbert, Johnson, and Keerthi (GJK) algorithm.

Find closest points of two convex shapes.
- A complex shape can be represented by a set of convex shapes.
- After the contact, GJK can’t find closest points, So...

\[ t = t_0 \quad \text{to} \quad t = t_1 \]

New closest points
Contact Analysis

- Contact part = Intersection of two convexes.
- For given two convex and a point in the intersection.
- Find the intersection.

Contact Analysis(2)

- Finding the intersection of two convex

Contact Analysis(3)

- Finding the intersection of two convex (2)

Integration of force

- Penalty force
- Dynamic friction force
- Maximum static friction force

Integration for a triangle

<table>
<thead>
<tr>
<th>Force from spring model:</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ f = k \int_{\text{prev}} h_n dS ]</td>
</tr>
<tr>
<td>[ = k \left( \frac{1}{36} (h_1 + h_2 + h_3) (p_1 + p_2 + p_3) + 3(h_3 p_1 + h_2 p_2 + h_1 p_3) \right) ]</td>
</tr>
</tbody>
</table>

Static friction force

<table>
<thead>
<tr>
<th>Spring-damper model for sliding constraint.</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ \tau = k \int_{\text{prev}} p \times h_n dS ]</td>
</tr>
<tr>
<td>[ = \frac{k}{36} \left( (h_1 + h_2 + h_3) (p_1 + p_2 + p_3) + 3(h_3 p_1 + h_2 p_2 + h_1 p_3) \right) ]</td>
</tr>
</tbody>
</table>

Integrate forces from distributed model for each triangle.
Evaluation

- Compare three simulators
  - Proposed
    - Penalty method
    - Distributed model.
  - Point based
    - Penalty method
    - A model on the most penetrating point.
  - Analytic
    - Analytical method
    - Open Dynamics Engine (Smith R. 2000)

Computation time

- Proposed simulator
- Point based method
- Analytical method

Stability on normal force

- A cube on a floor.
- Measure angular momentum.

Stick-slip motion

- State transition between static and dynamic friction makes stick-slip motion.

Motions of spinning tops with and without distributed friction

Result
Proposed a real-time rigid body simulator for haptic interaction
- Penalty method
- Fast update rate
- Pointed out a problem on a large contact area
  - Solved the problem by integrating penalty over the intersection area
  - Fast and accurate simulation was achieved.

Thank you for listening
- Source codes, demos, movies...
  
  [Link]

Dual Transformation
- Dual transformation transform a face into a vertex and a vertex into a face.
- Dual transformation’s dual transformation is original facet.