Bimanual Haptic Interaction with Virtual Environments

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Virtual Reality and Haptics

- **Virtual Reality** (VR): Immersion of a user in a Virtual Environment (VE)
- **Haptic sense**: Kinesthetic and tactile perceptions
- **Haptic devices**: Enhancing immersion in VR through tactile/force feedback

![Geomagic](Geomagic)
Bimanual Haptics

- Haptic applications often one-handed
- Common use of two hands in daily life
- **Bimanual haptics:** Haptic interaction with VEs through both hands

[Ullrich and Kuhlen, 2012]  [Faeth et al, 2008]
Challenges of Bimanual Haptics

Human aspects | Hardware | Software | Interaction

User

Haptic Interface

Interaction Techniques

Haptic Rendering

Virtual Environment
Objective

• **Objective:** Improving bimanual haptic interaction by enhancing:
  - Realism of interactions
  - Computational efficiency

• Three main axes:
  - Efficiency of soft hand models
  - Grasping with rigid models
  - Bimanual haptic interaction in VEs with rigid proxies
Related Work – Hardware

- Bimanual haptic devices
  - Single-point grounded
  - Single-point mobile
  - Multi-finger body-based
  - Multi-finger grounded

- Summary:
  - Mostly symmetrical devices
  - Limited workspaces (+ interface collision)
  - Wide range of degrees of freedom (DOF)

[Hulin et al., 2008]  [Peer and Buss, 2008]
[Formaglio et al., 2006]  [Walairacht et al., 2001]
Related Work – Physical Models

• Several hand representations:
  ▪ Point or rigid proxies
    [Zilles and Salisbury, 1995, Ruspini et al., 1997, Ortega et al., 2007]
  ▪ Rigid hand models
    [Borst and Indugula, 2005, Kry and Pai, 2006, Ott et al., 2007, Jacobs et al., 2012]
  ▪ Deformable hand models
    [Garre et al., 2011, Jacobs and Froehlich, 2011]

• Summary:
  ▪ Rigid models: Efficient, unrealistic contact, mostly unused for bimanual grasping
  ▪ Deformable models: More realistic contact, very high cost with two hands
Related Work – Contact Simulation

• Handling complex contact scenarios
  ▪ Contact reduction methods
    [Moravanszky and Terdiman, 2004, Kim et al., 2003]
  ▪ Separation of constraint sets
    [Miguel and Otaduy, 2011]
  ▪ Volume-based contact constraints
    [Allard et al., 2010]

• Summary:
  ▪ Rigid interaction: contact reduction well adapted
  ▪ Soft interaction: still many constraints to solve (e.g. friction)
Related Work – Grasping

- Grasping detection methods
  - Distribution of contacts between phalanges
    [Zachmann and Rettig, 2001, Moehring and Froehlich, 2005]
  - Relative position of contacts
    [Holz et al., 2008, Moehring and Froehlich, 2010]

- Grasping techniques
  - Controlling object motions with hand motions
    [Holz et al., 2008, Moehring and Froehlich, 2005, 2010]
  - “Soft finger” models for torsional friction
    [Barbagli et al., 2004, Ciocarlie et al., 2007]

- Summary:
  - Physically approximate methods
  - No techniques for bimanual grasping
Approach and Contributions

- Many contacts to solve with deformable hand models
  - Novel contact constraints for grasping
- Rigid models have unrealistic contact
  - Rendering of contact surfaces with rigid models
- Challenging exploration of VEs while grasping
  - Interaction techniques for bimanual haptics
- Realistic contact
- Efficient simulation
- Adapted hand models
- Stable grasping
- Exploration while grasping
- Navigation in large VEs
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Objectives

- **Objective:** Improving contact resolution with deformable hand models
- **Approach:** Reducing the number of contact constraints to be solved
- **Requirements:** Retaining the benefits of a fine contact sampling:
  - Pressure distribution
  - Torsional friction
Deformable Hand Model

Data glove (or scripted animations)

Tracked data

Articulated rigid body hand

Reduced coordinates model

FEM-based soft phalanges

Visual model

Collision model

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<td>index1Z</td>
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Unilateral spring

Unilateral mapping

Bilateral spring

Bilateral mapping
System for Bodies in Contact

• Dynamics of a discretized body in the simulation:

\[ M \ddot{\mathbf{v}} = f(q, \mathbf{v}) + f_{\text{ex}} \]

Mass matrix \hspace{1cm} Velocities \hspace{1cm} Internal forces \hspace{1cm} External forces

• Implicit Euler integration:

\[
\left( M - h \frac{\partial f}{\partial \mathbf{v}} - h^2 \frac{\partial f}{\partial \mathbf{q}} \right) d\mathbf{v} = hf(q_0, \mathbf{v}_0) + h^2 \frac{\partial f}{\partial \mathbf{q}} \mathbf{v}_0 + hf_{\text{ex}}
\]

• Two bodies in contact:

\[
A_1 d\mathbf{v}_1 = \mathbf{b}_1 + h \mathbf{H}_1^T \lambda \\
A_2 d\mathbf{v}_2 = \mathbf{b}_2 + h \mathbf{H}_2^T \lambda
\]

Matrix of constraint directions \hspace{1cm} Vector of constraint forces
Volume-based Separation Constraints

- **Objective:**
  Building a single separation constraint

- **Principle:**
  Volume contact constraint per phalanx
  [Allard et al., 2010]

- **Implementation:**
  - Evaluation of areas $S_i$ from the geometry
  - Penetrations $\delta_{n,i}^{\text{free}} \Rightarrow$ Volumes $V_i = S_i \delta_{n,i}^{\text{free}}$
  - Contact normals $n_i^T \Rightarrow$ Gradients $J_{V_i} = S_i n_i^T$
  - Volumes aggregated into a single constraint
Volume-based Separation Constraints

• For each contact point, contribution to the constraint matrix:

\[
\mathbb{H}_{n,i} = S_i n_i^T
\]

• Formulation of non-penetration law:

\[
\lambda_n \geq 0 \quad \sum J_{V_i} (q_0 + \Delta \dot{q}) \leq 0
\]

Constraint force repulsive or null
Penetration volume must not increase

• In position, removal of the penetration
Non-uniform Pressure Distribution

- **Objective:**
  Ensuring higher constraint forces for higher penetrations

- **Principle:**
  Weighting each contact contribution in the constraint matrix

\[ \mathcal{H}_{n,i} = w_i S_i n_i^T \]

- **Implementation:**
  Weights proportional to penetration

\[ w_i = \delta_{n,j}^{\text{free}} \left/ \left( \sum \delta_{n,j}^{\text{free}} / n_j \right) \right. \]
Aggregate Friction Constraints

- **Objective:**
  One set of constraints for friction

- **Principle:**
  2 tangential, 1 torsional [Contensou, 1963]

- **Implementation:**
  - Admissible values computed from $\Phi$
    [Leine and Glocker, 2003]
    \[
    \Phi = \sum_i \frac{S_i}{S} \mu \lambda_n \|v_s\| \quad \text{with } v_s \text{ sliding velocity at contact points } i
    \]
  - Tangential/torsional sticking when friction forces/torques within values
Results - Use cases

• Grasping a cube from the edges
• Full grasp of a rigid ball
• Spinning a pencil
• Real time interaction with a soft ball using a data glove
• Bimanual dumbbell lifting
Results - Performance

• Implementation: SOFA framework [Faure et al., 2012]

• With 176 contacts:
  ▪ Constraints / 10
  ▪ Constraint solving time / 4
  ▪ Simulation time - 60%

• In bimanual scenario:
  ▪ Constraint solving time / 2
  ▪ Simulation time - 26%

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Phalanges</th>
<th>Contacts</th>
<th>Constraints</th>
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<td></td>
<td></td>
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<td>Point</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>Aggr.</td>
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<tr>
<td>Rigid ball</td>
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<td></td>
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<tr>
<td>Dumbbell</td>
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<td>Pen spinning</td>
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<td>13</td>
<td>37</td>
</tr>
<tr>
<td>Edge grasping</td>
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<td>12</td>
<td>37</td>
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<td></td>
<td></td>
<td>21</td>
<td>65</td>
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<table>
<thead>
<tr>
<th>Scenario</th>
<th>Constraint solving (ms)</th>
<th>Total time (ms)</th>
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</thead>
<tbody>
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<tr>
<td>Rigid ball</td>
<td>24,73</td>
<td>9,44</td>
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<tr>
<td>Dumbbell</td>
<td>223,69</td>
<td>54,75</td>
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<tr>
<td>Pen spinning</td>
<td>4,2</td>
<td>2,32</td>
</tr>
<tr>
<td>Edge grasping</td>
<td>9,64</td>
<td>2,23</td>
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<td></td>
<td>23,01</td>
<td>3,45</td>
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Conclusion

• Novel constraint formulation for soft finger contact **minimizes the number of constraints** per phalanx

• Weighting method to **retain pressure distribution** over the surface

• Coulomb-Contensou friction law to maintain **torsional friction without additional constraints**

• **Real time grasping of objects** with deformable hand models
Approach and Contributions

- Realistic contact
- Efficient simulation

- Many contacts to solve with deformable hand models

- Novel contact constraints for grasping

- Rigid models have unrealistic contact

- Rendering of contact surfaces with rigid models

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Objectives

• **Objective:** More efficient contact compared to:
  - Rigid interaction:
    + Fast computation
    - No surface
  - Soft body interaction:
    + Finger deformation
    - Slow soft body computation

• **Approach:** Heuristic method to render contact surfaces
God-finger Method

• Propagation of a contact surface from an initial contact point

• Two main steps:
  ▪ Generation of a fingerprint
  ▪ Fitting of the surface on the object geometry

• Contact surface described by *sub-god-objects*
Fingerprint Generation

- **Objective:**
  Guide for the propagation

- **Principle:**
  Generation of *radial vectors* from the initial contact

- **Implementation:**
  - With multiple contacts, generation from the centroid
  - Radial tree for uniform distribution
  - Elliptic surface for 6DOF interfaces
Local Geometry Scan

- **Objective:**
  Propagating on the surface

- **Principle:**
  Scan of the local geometry following the *radial vectors*

- **Implementation:**
  - The scan stops with:
    - Length of the radial vector
    - Sharp edges
    - Normals exceeding friction cone
  - For rough surfaces, keep scanning after sharp edges
Results

• Implementation: Havok Physics

• Simulation rate: 1000 Hz

• Unimanual manipulation
  ▪ Better control of rolling
  ▪ Possibility of lifting objects

• Bimanual manipulation
  ▪ Better control around the grasping axis
Conclusion

- **God-finger** method: rendering of finger pad-like contact surfaces from point or rigid contacts
- **Stabilization of contact and bimanual grasps** with better constraining of the rotation of virtual objects
- **Low cost** allowing for haptic rates
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Objectives

• Solving main issues with bimanual haptic interaction using single-point devices
  ▪ Exploration of VEs with limited workspaces
  ▪ Handling of virtual objects with simple rigid proxies
  ▪ Simultaneous exploration and manipulation
**Double Bubble**

- **Objective:**
  Exploration of VEs with two haptic devices

- **Principle:**
  Position/rate control scheme for each bubble
  
  [Dominjon et al., 2005]

- **Implementation:**
  - Non-spherical workspaces
  - Invisible plane to keep the hands from crossing
Viewport Adaptation

- **Objective:**
  Keeping the proxies in the field of view

- **Principle:**
  Viewpoint adaptation

- **Implementation:**
  - Translation: adaptation to the *bubble* positions and widths
  - Rotation: Separation plane as a “revolving door”
Joint Control

- **Objective:**
  Facilitating grasping with *bubbles*

- **Principle:**
  - Same bubble size
  - Same rate control velocities

- **Implementation:**
  - Intersection of *bubbles*
  - Average of velocities
Grasping Detection

• **Objective:**
  Detect grasping attempts

• **Principle:**
  Detection based on:
  - Forces applied on the object
  - Relative position of the hands

• **Implementation:**
  - Force threshold on contacts
  - Ray casts between both hands with a tolerance
Magnetic Pinch

• **Objective:** Providing assistance to the user when grasping objects

• **Principle:** Visual and haptic effect of “magnetism” between hands and object

• **Implementation:**
  - Springs: softer, 3DOF
  - Constraints: harder, 6DOF
Evaluation

• Task: picking and carrying

• 4 conditions:
  ▪ Control: *clutching* technique
  ▪ Exploration: *double bubble*
  ▪ Manipulation: *magnetic pinch*
  ▪ All proposed techniques

• 13 participants

• 4 conditions × 4 targets × 11 trials = 176 trials

• Collected data:
  Completion times, number of drops, subjective questionnaire
Results

- Friedman test: significant effect of the techniques
- Completion times:
  - Manipulation-only improve over control and exploration-only
  - Further improvement with all techniques
- Object drops:
  - Improvement with both manipulation conditions
Subjective Questionnaire

• The conditions with manipulation techniques were overall better appreciated by the participants

• The addition of the magnetic effect did not lead to significant changes in the Realism criterion
Conclusion

• **Double bubble** with viewport adaptation: **smooth bimanual exploration** of VEs

• **Joint control**: easier grasping with the **double bubble**

• **Magnetic pinch**: assistance to the user when **manipulating objects**

• User experiment on carrying task: **faster completion, less drops, better user appreciation**
Conclusion

• Objective: Improving interaction in VEs using two haptic devices

• Three main contributions:
  ▪ Aggregate constraint method for improving contact resolution with deformable hands
  ▪ Heuristic method for rendering of finger pad contact surfaces with point and rigid proxies
  ▪ Novel interaction techniques for bimanual exploration in VEs and haptic manipulation with single-point haptic devices
Perspectives

• Contact constraint formulation for soft hand grasping
  ▪ Improving the hand model with the palm and non-linear deformation
  ▪ Comparison against other contact reduction methods

• Rendering of finger pad contact surfaces
  ▪ Generation of arbitrary-shaped surfaces (e.g. palm)
  ▪ More realistic visual feedback (visual finger deformation, etc.)

• Interaction techniques for bimanual haptics
  ▪ Adaptation for immersive interaction and multiple objects
  ▪ Further evaluations on different tasks and between the variants

• Applications: virtual assembly, surgical training, rehabilitation
Publications

• **Journal papers**

• **Book chapters**

• **International conferences**

• **National conferences**
Thank you for your attention

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