Fast Proximity Queries for Haptic Rendering & Applications

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Proximity Queries for Force Display

- **Contact or restoring forces are generated to prevent penetration into a virtual object**
  - **Find the separation distance between objects to estimate the time of impact**
  - **Detecting if a collision or penetration has occurred**
  - **Determining the (projected) contact point on the object surface**
  - **Computing penetration depth to calculate contact force**

Bounding Volume Hierarchies

- **Sphere [Hubbard93, QuinLan94]**
- **Axis-Aligned Bounding Boxes [Beckman90, Cohen95, Held95]**
- **Oriented Bounding Boxes [Gottschalk96, Barequet96]**
- **Spherical Shells [Krishnan98]**
- **K-dops [Klosowski96]**

Spatial Partitioning

- **Uniform or Adaptive Grids**
- **Octrees**
- **K-d Trees**
- **BSP Trees**

Frame-to-Frame Coherence

- Baraff [SIGGRAPH'1990]
- Lin & Canny [ICRA'1991]
- Cohen, Lin, Manocha & Ponamgi [I3D'1995]
- Cameron [ICRA'1997]

Performance Requirements

- Interactive Performance (kHz rate)
- Scalability
- Generality

Other issues ……

- Robustness
- Data Representation
- Close Proximity & Multi-Contacts

Organization

- *H-COLLIDE*
- 6-DOF Haptic Rendering
- Applications: inTouch & DAB
- Ongoing Related Work
- Future Research Directions

Problem Characteristics

- Little movement in < 1 millisecond $\Rightarrow$ high motion coherence
- Potential contact region is localized

HCOLLIDE: Themes

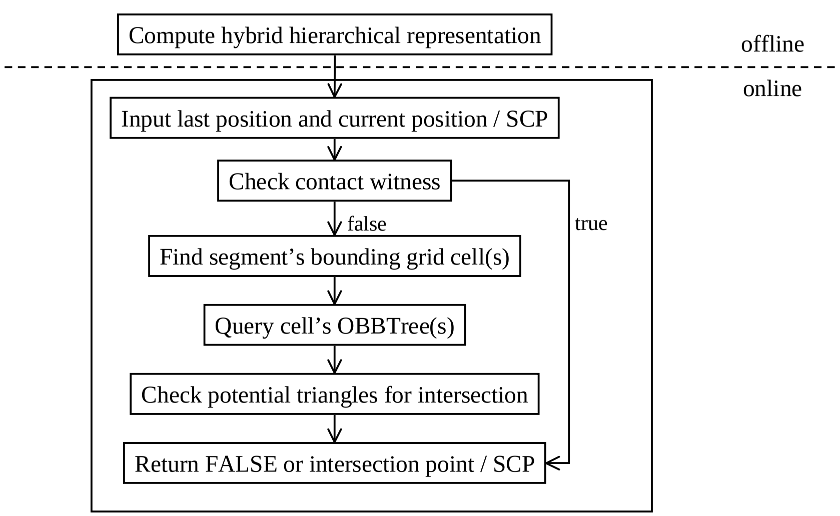
- Spatial Decomposition
  - Uniform grid implemented using hashing
- Bounding Volume Hierarchy
  - Oriented bounding box trees
- Frame-to-Frame Coherence
  - Caching the last “witness”

Gregory, Lin, Gottschalk, Taylor [VR’99, CGTA’00]

HCOLLIDE: Algorithm Overview

- OFFLINE PROCESS
  - Pre-compute hybrid representation, consisting of uniform grids and each contains an OBBTree.
- RUNTIME PROCESS
  - Identify “contact region” by uniform spatial partitioning (implemented with hash table)
  - Locate the exact contact points by querying and traversing the OBBTrees using a specialized “Separating Axis Theorem”
  - Frame-to-frame coherence by caching the last “witness”
  - Find the projected surface contact point

HCOLLIDE: System Architecture



H-Collide: Implementation

- Written in C++
- Interfaced with *GHOST* (beta 2.0) and a 3-DoF PHANToM arm
- Timing obtained on 400 MHz Dual-Processor Pentium II with 1G memory

HCOLLIDE: Algorithm Comparison

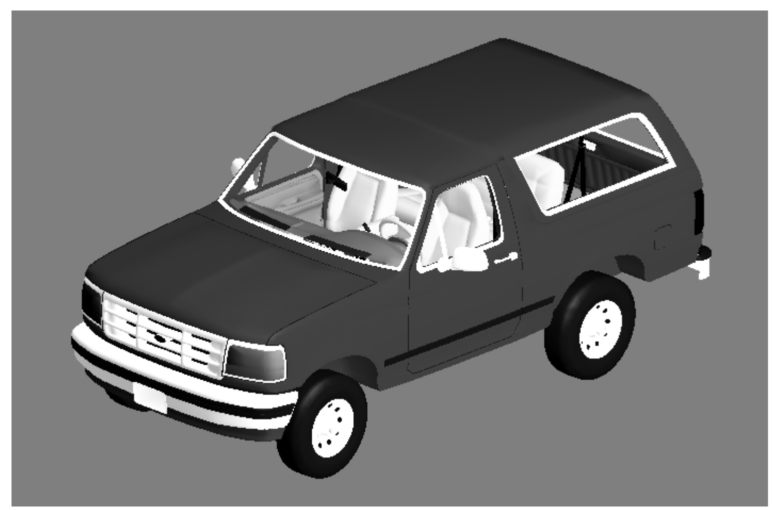
- Adaptive Grids
- Hybrid Method (H-Collide)
- Bounding Volume Hierarchy (OBBTrees)
- *GHOST* (BSP)

Nano-Surfaces

HCOLLIDE: Timing on Nano-Surfaces

Method	Hash Grid	Hybrid	OBB Tree	Ghost
Ave Col. Hit	0.0138	0.0101	0.0134	0.332
Worst Col. Hit	0.125	0.168	0.0663	0.724
Ave Col. Miss	0.00739	0.00508	0.00422	0.0109
Worst Col. Miss	0.0347	0.0377	0.0613	0.210
Ave Int. Hit	0.0428	0.0386	0.0447	0.0851
Worst Int. Hit	0.0877	0.102	0.0690	0.175
Ave Int. Miss	0.0268	0.0197	0.0213	0.0545
Worst Int. Miss	0.0757	0.0697	0.0587	0.284
Ave. Query	0.022	**0.016**	0.039	**0.18**

Ford Bronco



HCOLLIDE: Timing on Ford Bronco

Method	Hash Grid	Hybrid	OBB Tree	Ghost
Ave Col. Hit	0.0113	0.00995	0.0125	0.104
Worst Col. Hit	0.136	0.132	0.177	0.495
Ave Col. Miss	0.0133	0.00731	0.0189	0.0280
Worst Col. Miss	0.128	0.0730	0.137	0.641
Ave Int. Hit	0.0566	0.0374	0.609	0.0671
Worst Int. Hit	0.145	0.105	0.170	0.293
Ave Int. Miss	0.0523	0.0225	0.0452	0.0423
Worst Int. Miss	0.132	0.133	0.167	0.556
Ave. Query	0.027	**0.014**	0.028	0.048

Butterfly

HCOLLIDE: Timing on Butterfly

Method	Hash Grid	Hybrid	OBB Tree	Ghost
Ave Col. Hit	0.0232	0.0204	0.0163	1.33
Worst Col. Hit	0.545	0.198	0.100	5.37
Ave Col. Miss	0.00896	0.00405	0.00683	0.160
Worst Col. Miss	0.237	0.139	0.121	3.15
Ave Int. Hit	0.228	0.0659	0.0704	0.509
Worst Int. Hit	0.104	0.138	0.103	1.952
Ave Int. Miss	0.258	0.0279	0.0256	0.229
Worst Int. Miss	0.0544	0.131	0.0977	3.28
Ave. Query	0.030	**0.016**	0.016	**0.32**

HCOLLIDE: Algorithm Analysis

- **Applicable to unstructured data sets with no connectivity information**
- **At least 3-20 times faster than *GHOST* on the models we have tested on**
- **Hybrid is the most favorable and capable of maintaining kHZ rate**
- **If the number of triangles per grid cell is relatively small compared to the model size, then hybrid method runs in *constant time***

Organization

- H-COLLIDE
- *6-DOF Haptic Rendering*
- Applications: inTouch & DAB
- Ongoing Related Work
- Future Research Directions

6-DoF vs 3-DoF Haptic Rendering

- Force/torque feedback vs. force display
- Object-object vs. point/line-object contact
- Multiple vs. single surface contacts
- Geometry driven instability due to cavity in 6-DoF

Trade-Offs

- Accept limited accuracy for speed
- Assume static environments with only one moving object & one contact to achieve constant time query
- Use simple force model and has force magnitude discontinuity

McNeely, Puterbaugh & Troy [SIGGRAPH'99]

UNC's 6-DOF Haptic Display

- Applicable to (modestly) dynamic enviornments
- Exact and accurate contact determination
- Smooth collision response

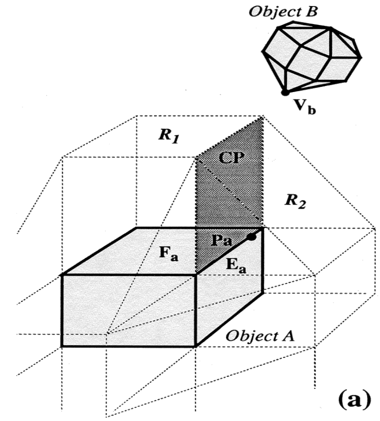
Gregroy, Mascarenhas, Ehmann, Lin & Manocha [VIS'2000]

Contact Determination

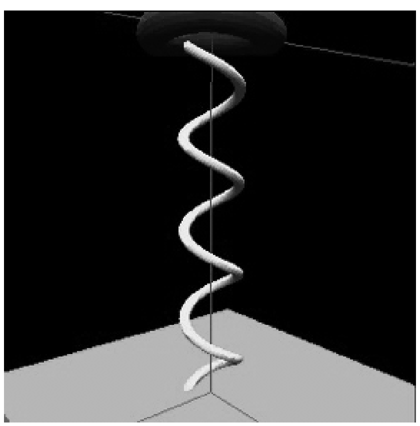
- *Sweep & Prune* to reduce pairwise tests
- Construct hierarchy of convex pieces
  - Based on surface decomposition
- *SWIFT*++ for exact collision detection
  - Constant time per query for convex pieces
  - Lookup table for quick initialization
  - Acceleration techniques exploiting coherence

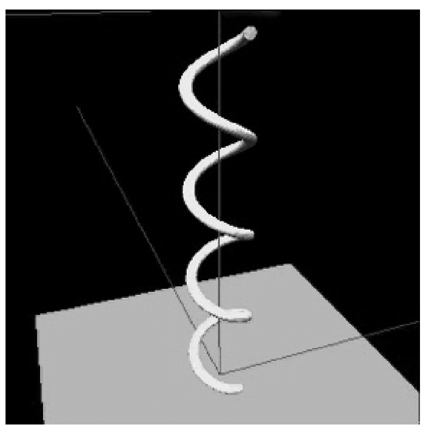
Constant-Time Collision Check

- Closest feature tracking using Voronoi regions



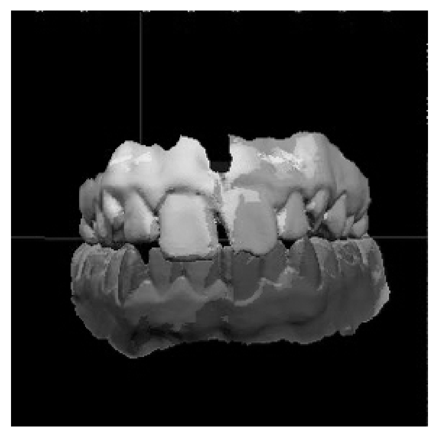
SWIFT & SWIFT++

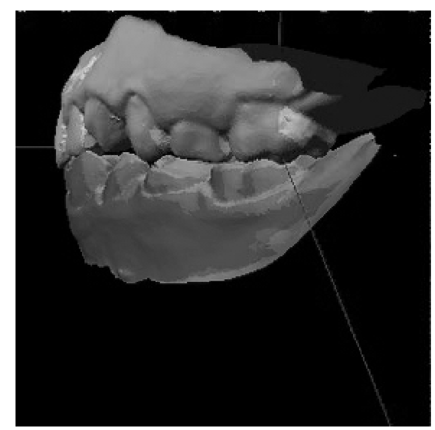




- Multiresolution Techniques + Coherence
  Ehmann & Lin [IROS'00, EG'01]

SWIFT++: Simulation of Jaw Motion





- http://www.cs.unc.edu/~geom/SWIFT++

Real-Time Constraint

N: total number of convex pieces
K: number of near contacts (bnding-box overlaps)
M: number of actual contacts
t_s: time for sweep & prune
t_c : upper bound on collision check
t_f: computing time of forces/torques

- Total haptic rendering time bounded by:

$$T_h = N \times t_s + K \times t_c + M \times t_f$$

Real-Time Scheduling

- Pairs of objects were in contact last frame are given highest priority
- Prioritize the remaining pairs based on approximated time to collision using distance computation

Restoring Forces & Torques

- Penalty-based contact force:

$$\mathbf{F}_r = k_s D_p$$

- Torque is computed by

$$\boxed{T_r = k_t \theta_r}$$

$$\mathbf{T}_r = \sum_i \mathbf{F}_{ri} R_i$$

Other Techniques

- Virtual Proxy
- Predictive Collision Response
- Force/Torque Interpolation

Predictive Collision Response & Virtual Proxy

- **Calculating δ:**

$$\delta = v_c \times \Delta t$$

- **When $d < \delta$,**

$$F_r = k_s(\delta - d)$$

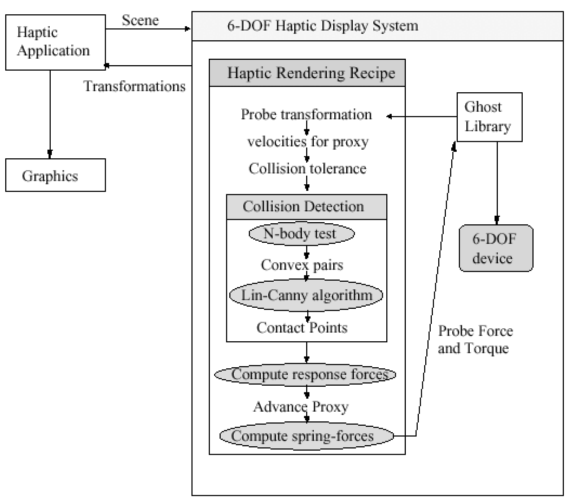
- **When penetration of D_p occurs,**

$$F_r = k_s(\delta + D_p)$$

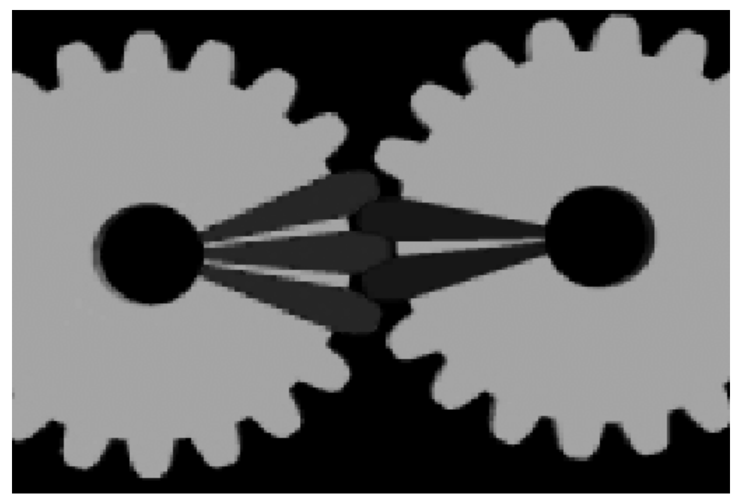
Force/Torque Interpolation

if $(F_1 - F_0) > 2F_{max}$
then $F_1 = F_0 + F_{max}$
else if $F_1 - F_0 > F_{max}$
then $F_1 = (F_0 + F_1)/2$
DISPLAY F_1

System Architecture



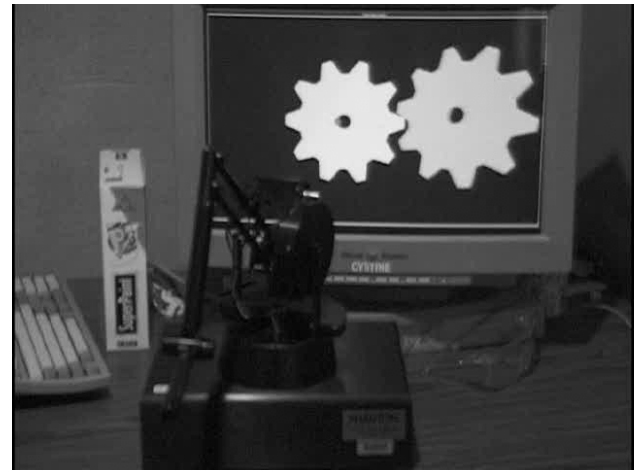
Gear Interactions



Timings of System Components

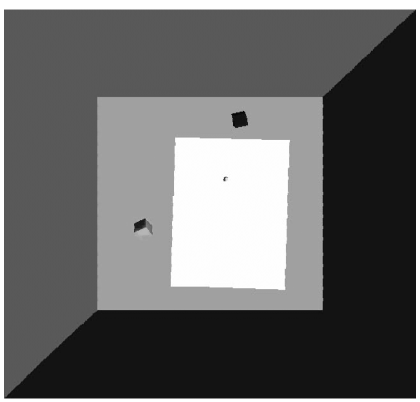
System component	Time (ms)
Number of updates = 12499	
Worst Time	0.34300
Average Time	0.178922
Total Col. Det. tests = 12499	
Average Col. Det. time	0.071615
Total N-body tests = 7285	
Average N-body time	0.040022
Total Exact CD tests = 38989	
Average Exact CD time	0.001291
Total number of collisions = 10870	
Average Response time	0.092331

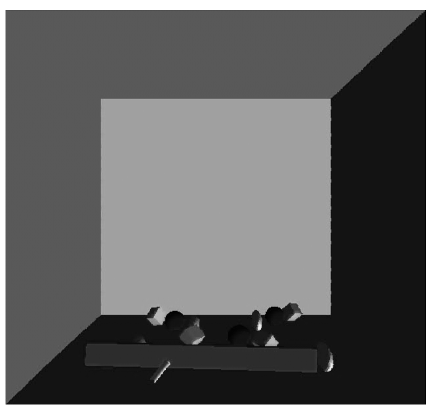
System Demonstration



Force/Torque Display of Mechanical Interaction Between Gears

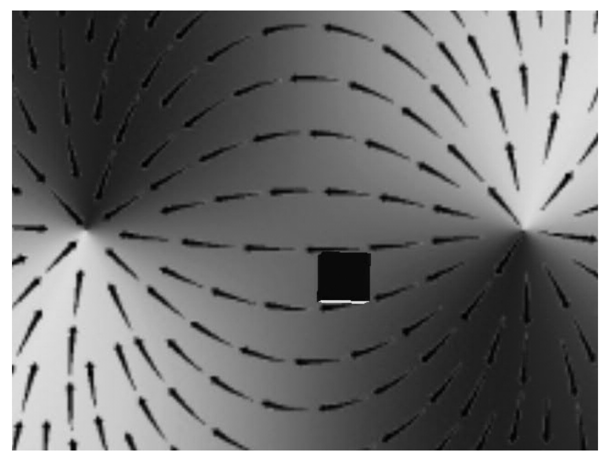
Interacting with a Dynamic Environment using Haptic Control





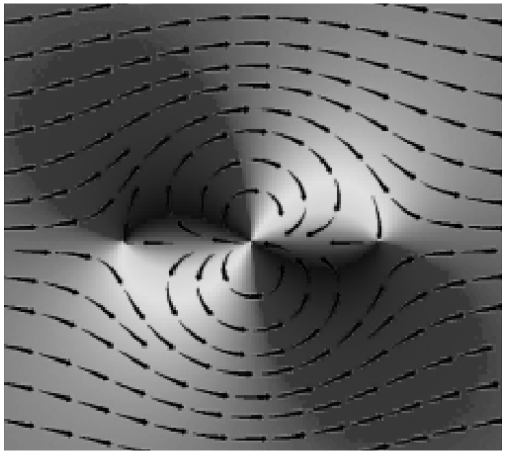
http://www.cs.unc.edu/~geom/6DHaptics

Haptic Visualization of Force Fields



Force Field Generated by Two Charges of Opposite Polarity

Haptic Visualization of Force Fields



Force Field of Ideal Flow around and inside a Cylinder

Organization

- H-COLLIDE
- 6-DOF Haptic Rendering
- *Applications: inTouch & DAB*
- Ongoing Related Work
- Future Research Directions

inTouch: Motivation

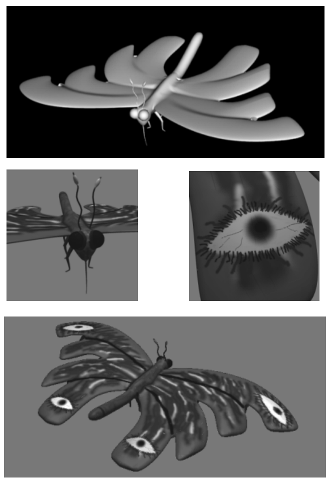
- Lack of direct model interaction with traditional 2D interface used by current modeling packages
- Difficulty in rotating an object, mapping and registration to determine location of surface in 3D relative to mouse pointer, while performing 3D painting
- High learning curve resulted from typical 2D input deter creative expressions in model creation and artistic design

inTouch: Highlights

- Direct Haptic Interaction
- Multiresolution Modeling
- 3D Painting on Polygonal Meshes

Gregroy, Ehmann, Lin [VR'2000]

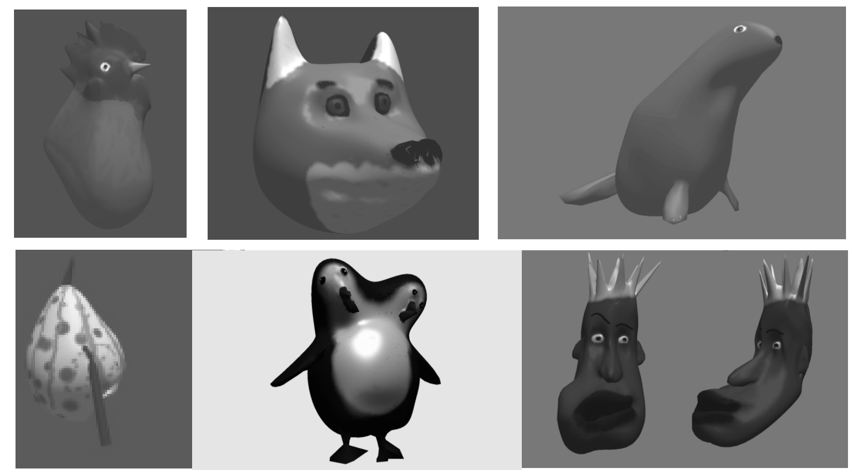
Models Painted using *inTouch*



Painted Butterfly (~80k triangles)

http://www.cs.unc.edu/~geom/inTouch

Models Created using *inTouch*



http://www.cs.unc.edu/~geom/inTouch

inTouch: System Demonstration

DAB: Interactive Haptic Painting with 3D Virtual Brushes

- **The system provides the traditional tools of the painter: canvas, palette, brush and paint.**
- **A force feedback 6-DOF stylus provides a haptic interface to these tools.**
- **Complex brush strokes can be created intuitively using a 3D physically-based, deformable brush with a bi-directional paint transfer model**

Baxter, Scheib, Lin & Manocha [SIGGRAPH 2001]

Original Art Painted Using *DAB*

http://www.cs.unc.edu/~geom/DAB

DAB: System Demonstration

Organization

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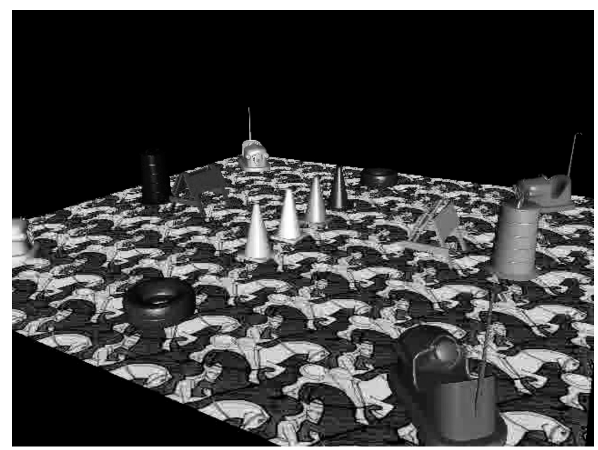
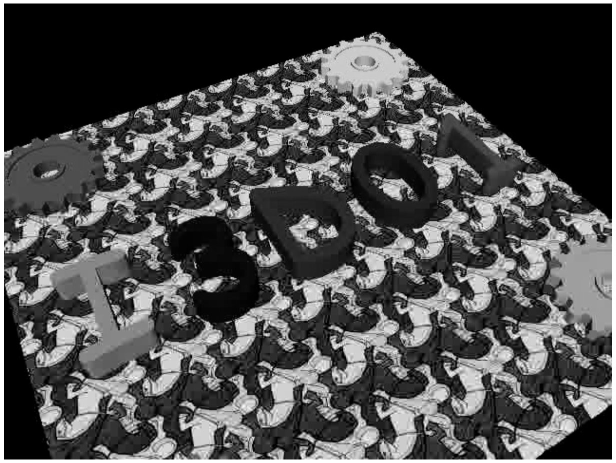
- *Ongoing Related Work*
- Future Research Directions

Recent Results: PIVOT



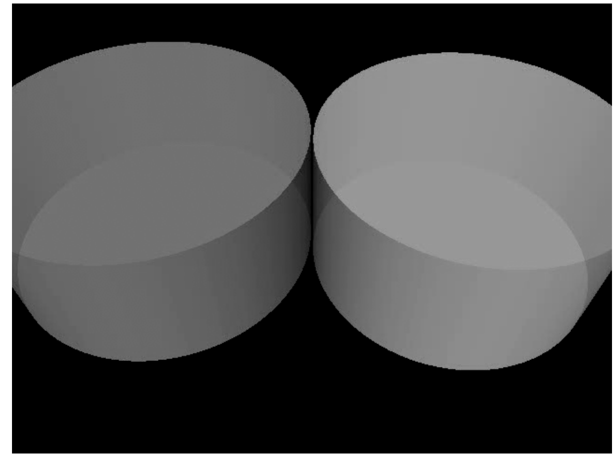
Proximity Queries Using Graphics Hardware Acceleration
Hoff, Zaferakis, Lin & Manocha [I3D'01]

PIVOT: Simulation of Randomly Moving Gears & Letter Blocks



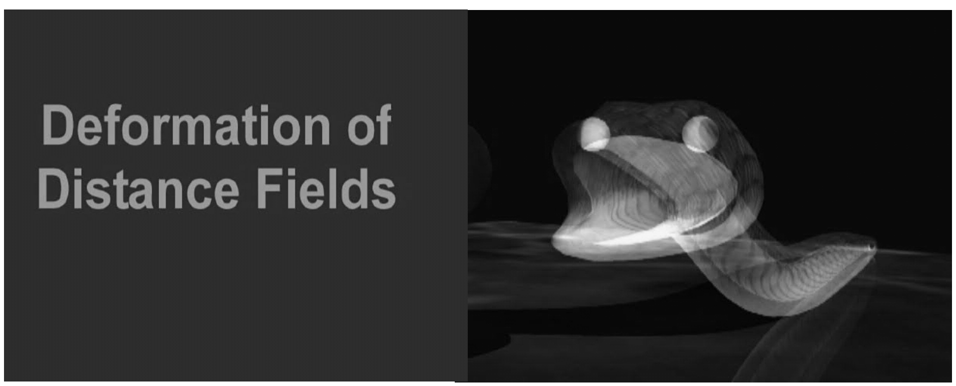
http://www.cs.unc.edu/~geom/PIVOT

PIVOT: Deformation of Jello



http://www.cs.unc.edu/~geom/PIVOT

Recent Results: Deformed Distance Fields (DDF)



http://www.cs.unc.edu/~geom/DDF

Fisher & Lin [EG/CAS'01]

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Future Research Directions

6-DOF Haptic Rendering:

- Algorithms for processing more complex geometry (non-rigid, high number of primitives, more moving entities, etc.)
- Rendering of textured surfaces
- Better integration of visual and haptic cues:

  http://www.cs.unc.edu/~geom/HView

Future Research Directions

inTouch:

- Adding more texture/image operations: **http://www.cs.unc.edu/~geom/*ArtNova***
- Experimenting with different UI paradigm
- Conducting extensive user study
- Extension to 6-DoF haptic devices
- Other deformation controls
- Incorporating 3D brush models

Future Research Directions

DAB:

- **Improved physical models for brush deformation & bristle effects**
- **Haptic rendering of surface texture**
- **Additional painting tools, artistic media, and a greater diversity of paint models**
- **Addition of various non-physical effects**

Future Research Directions

Applications:

- Arts & Design
- Image Segmentation
- Scientific & Engineering Visualization
- Surgical Training
- Virtual Prototyping

Collaborators

- Bill Baxter
- Stephen Ehmann
- Susan Fisher
- Stefan Gottschalk
- Arthur Gregory
- Kenneth Hoff II
- Dinesh Manocha
- Ajith Mascarenhas
- Vincent Scheib
- Russell Taylor
- Andrew Zaferakis

Acknowledgements

- Lauren Adams
- Eriko Baxter
- Sara Hoff
- Rebecca Holmberg
- Greg Turk
- Other UNC-CH users and visitors

Acknowledgements

- Army Research Office
- Department of Energy
- Division Inc.
- National Science Foundation
- Office of Naval Research
- Intel

The End