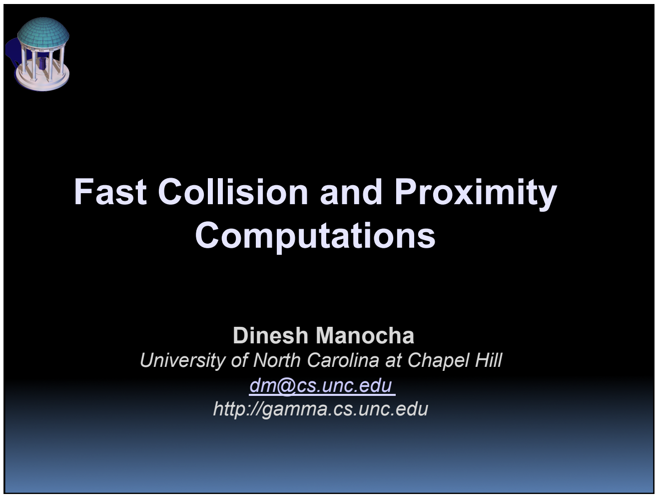

Fast Collision and Proximity Computations

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Collaborators

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- Min Tang (Zhejiang Univ.)
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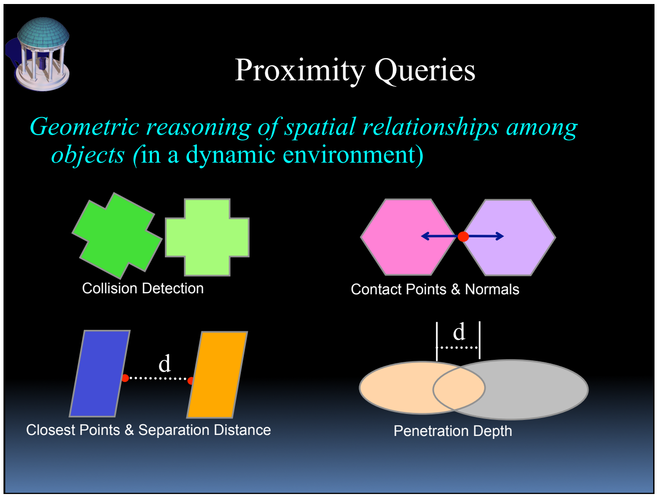


Proximity Queries

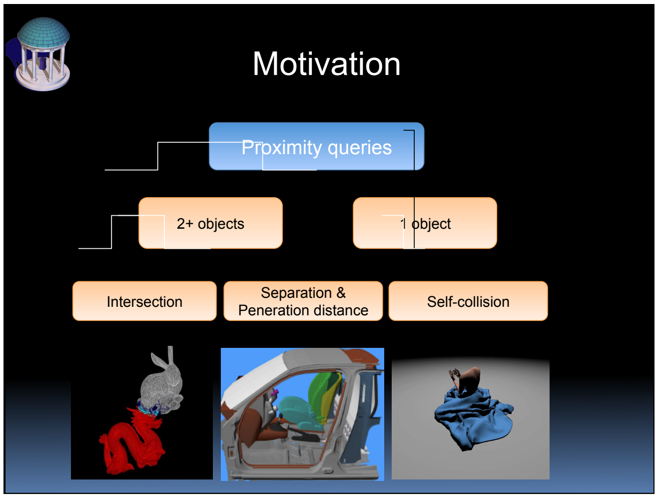
*Geometric reasoning of spatial relationships among objects (*in a dynamic environment)

Collision Detection

Contact Points & Normals

Closest Points & Separation Distance

Penetration Depth



Motivation

Proximity queries

2+ objects

1 object

Intersection

Separation & Peneration distance

Self-collision

Problem Domain Specifications

Model Representations
- polyhedra (convex vs. non-convex vs. soups)
- CSG, implicits, parametrics, point-clouds

Type of Queries
- discrete vs. continuous query
- distance vs. penetration computation
- estimated time to collision

Simulation Environments
- pairwise vs. n-body
- static vs. dynamic
- rigid vs. deformable

Applications

- Robot motion planning
- Simulation of (dis-)assembly tasks
- Tolerance verification
- Simulation-based design
- Ergonomics analysis
- Haptic rendering
- Physics-based modeling and simulation

Prior work on Proximity Computations

- Fast algorithms for convex polytopes (1991 onwards)
- Bounding volume hierarchies for general polygonal models (1995 onwards)
- Deformable models & self-collisions (2000 onwards)
- Multiple software systems

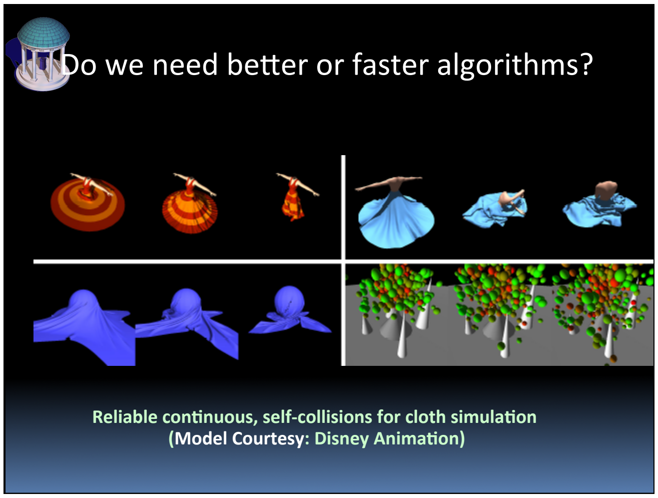
I-Collide, RAPID, PQP, DEEP, SWIFT, SWIFT++, PIVOT
DeformCD, Self-CCD,…..

Prior work on Proximity Computations

Multiple software systems

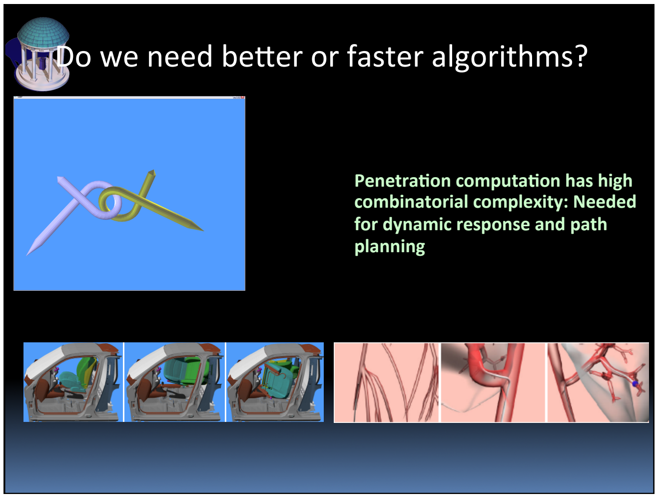
- I-Collide, RAPID, PQP, DEEP, SWIFT, SWIFT++, DeformCD, PIVOT, Self-CCD,…..
- More than 100,000 downloads from 1995 onwards
- Issued more than 50 commercial licenses (Kawasaki, MSC Software, Ford, Sensable, Siemens, BMW, Phillips, Intel, Boeing, etc.)

Do we need better or faster algorithms?



Do we need better or faster algorithms?

Reliable continuous, self-collisions for cloth simulation
(Model Courtesy: Disney Animation)



Do we need better or faster algorithms?

Penetration computation has high combinatorial complexity: Needed for dynamic response and path planning

Do we need better or faster algorithms?

Finite-Element Simulation for Crash Analysis: Collisions can take 50-90% of simulation time (Model Courtesy: BMW & LS-DYNA)

Our Recent Work

- Faster algorithms for continuous collision detection among deformable models
- Volumetric continuous collision methods
- Penetration depth computation
- Parallel algorithms for multi-core and many-core processors

---

Continuous Collision Detection

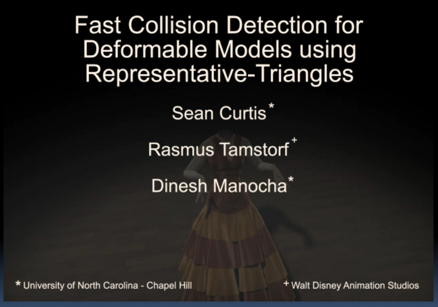
Compute the first time of contact between discrete time intervals

- Incremental hierarchy based methods
- Improved culling based on normal bounds
- Eliminate redundant elementary tests
- Simple filters to remove false positives

More than 10-20X improvement in performance

[Tang et al. 2008, Curtis et al. 2008, Tang et al. 2010]

Continuous Collision Detection



Fast Collision Detection for Deformable Models using Representative-Triangles

Sean Curtis*

Rasmus Tamstorf+

Dinesh Manocha*

* University of North Carolina - Chapel Hill

+ Walt Disney Animation Studios

Volumetric CCD

- New volumetric methods for FEM simulations
- Collision checking between internal nodes and elements
- Eliminate redundant elementary tests
- Simple filters to remove false positives

Up to 20X improvement in performance

[Tang et al. 2011]

Volumetric CCD

VolCCD: Fast Continuous Collision Culling between Deforming Volume Meshes

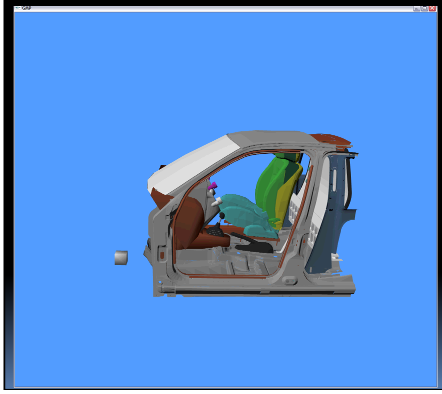
Submission ID: 0191

Penetration Depth Computation

- Generalized penetration depth formulation based on rotational motion
- Local and global penetration depth computation
- Retraction based planners for rigid and articulated models

[Zhang et al. 2006; Zhang et al. 2007; Zhang et al. 2008; Pan et al. 2010]

Retraction-based Planner using Penetration Depth Computations



Collision or proximity checking takes more than 90% of time in sample-based planners

---

A Parallel Revolution: 2005 Onwards

Power Wall = Brick Wall

End of way built microprocessors for last 40 years

→New Moore's Law is 2X processors ("cores") per chip every technology generation, but ≈ same clock rate

"This shift toward increasing parallelism is not a triumphant stride forward based on breakthroughs …; instead, this … is actually a retreat from even greater challenges that thwart efficient silicon implementation of traditional solutions."

The Parallel Computing Landscape: A Berkeley View, Dec 2006

- Sea change for HW & SW industries since changing the model of programming and debugging

Parallel Revolution has started!

- While evolution and global warming are “controversial” in scientific circles, belief in need to switch to parallel computing is unanimous in the hardware community

  (Dave Patterson, Berkeley)

- AMD, Intel, IBM, Sun, … now sell more multiprocessor (“multicore”) chips than uniprocessor chips
  - Plan on little improvement in clock rate (8% / year?)
  - Expect more cores every 2 years, ready or not
  - Note – they are already designing the chips that will appear over the next 5 years, and they’ re parallel

---

Multi-Core and Many-Core Processors

- Multi-core CPUs (Intel, AMD, IBM)
  - Take the best serial core and fit as many cores on a single chip, as possible
  - Each serial core has large caches
  - Support limited SIMD and instruction-level parallelism

Many-Core Processors (GPUs)

2010: Fermi has 512 *scalar* fragment processors or cores
2009:GT285 240 *scalar* fragment processors or cores
2006:G80 (8800 GTX) has 128 fragment processors or cores
2005:G71 (7900) has 48 *vec4* pixel cores
2004: NV40 (6800) has 16 vec4 cores
2003: NV30 (5800) had 4 vec4 pixel shader pipes or cores

- Growth Rate of NVIDIA GPUs (2003 onwards)

Many-Core or High-Throughput Computing

- Notion of designing commodity processors with tens or hundreds of cores
- Combining fine-grain and coarse-grain parallelism
- High parallel code performance
- Improved memory throughput and power efficiency

GPU-based Algorithms

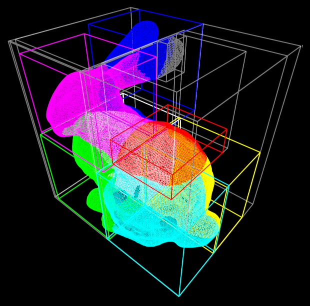
- Challenges in exploiting multiple cores
- Communication and synchronization between the cores is limited
- Limited cache hierarchy
- Use high number of threads to hide memory latency

High GPU Computing Throughput

- Provide a sufficient number of parallel tasks so that all the cores are utilized
- Provide several times that number of tasks just so that each core has enough work to perform while waiting for data from slow memory accesses

Dynamic GPU Work Distribution Methods [Lauterbach, Mo and Manocha 2009; Lauterbach & Manocha 2010]

Computing and Traversing Hierarchies

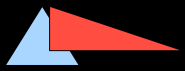


Hierarchy-based proximity queries

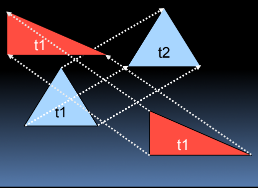
- Build or update hierarchies (Hard to parallelize)
- Traverse hierarchies recursively
  - Start with root nodes
  - Do nodes overlap?
    - **Yes:** Inner nodes: recurse on combinations of children
      Leaf nodes: put primitive pair in separate queue
  - Perform primitive overlap tests (Easy to parallelize)

Primitive tests

- Discrete collision: triangle-triangle test
  - Do triangles overlap?

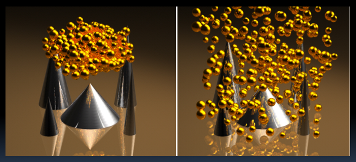


- Continuous collision
  - Did moving triangles overlap at any time between t1 and t2?



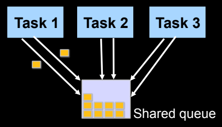
Related work

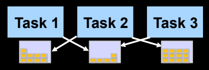
- Use multi-core CPUs
  - [Kim et al. 08, Kim et al. 09, Tang et al. 09]



Work organization on GPUs

- Standard for recursive hierarchy operations
  - Global work queue, work stealing





- Problem
  - Shared access on GPU only via slow, non-consistent global memory

Lightweight balancing

- Our solution
  - Every thread/core has local queue (non-shared)
  - Keep track of other thread's state occasionally
    - One shared global idle counter
  - If above threshold, break and balance queues

- Avg. ~2-3x performance of work stealing

Parallel Hierarchy Operations

- Can also use vector units
  - Each vector lane handles one intersection pair
  - Potentially thousands of parallel tests
- Local work queue shared between lanes
  - Access synchronized by atomics or prefix sum
  - Does not change outside synchronization

Hierarchy Construction

BVH construction on GPUs

  Uses thread and data parallelism

  Fast linear BVH construction

Interactive construction on current GPUs

Hierarchy Construction

Top-down methods

  E.g. recursively split primitives in half

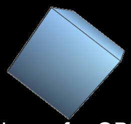
Bottom-up methods

  Repeatedly combine primitives into groups

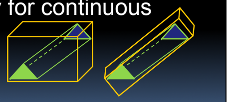
Derive from scene graph

Bounding volumes

- We use oriented bounding boxes (OBBs) on GPUs
  - Operations: about 1-2 order of magnitude more instructions

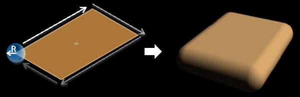


- But:
  - Hierarchy construction only ~25% slower for OBBs
  - Better culling efficiency (fewer overall tests)
  - Overall performance win (especially for continuous collision and distance queries)



Bounding volumes

- Separation distance:
  Rectangular swept spheres (widely used in PQP)



  - Also has expensive construction
  - Similar advantages, easy extension of OBBs

Front tracking

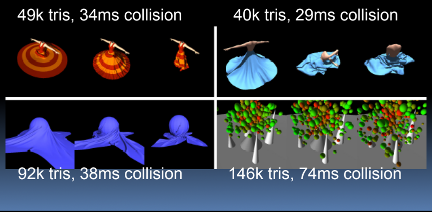
- Exploit temporal coherence
  - Simulations typically have small timesteps
- Store last intersecting pair for each subtree
- Next frame: still intersecting?
  - Yes: test primitives
  - No: go up in tree until intersection found

Front tracking

- Advantage
  - Less steps in intersection
  - Not necessarily less work, but results in higher parallelism
- Overall
  - ~10-25% less overall time for our benchmarks

Results

- Implemented in CUDA on NVIDIA GTX 285
  - Hierarchies built and updated fully on GPU
- Self-collision
  - Includes collision and update of BVH per frame
  - 10-20X speedup over CPU-based algorithms

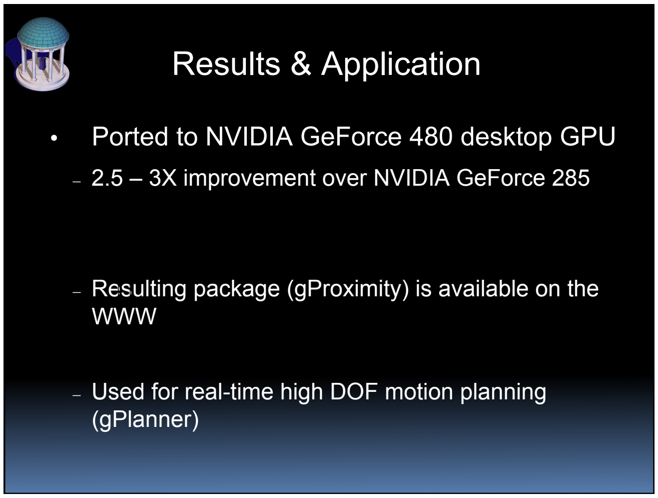


49k tris, 34ms collision

40k tris, 29ms collision

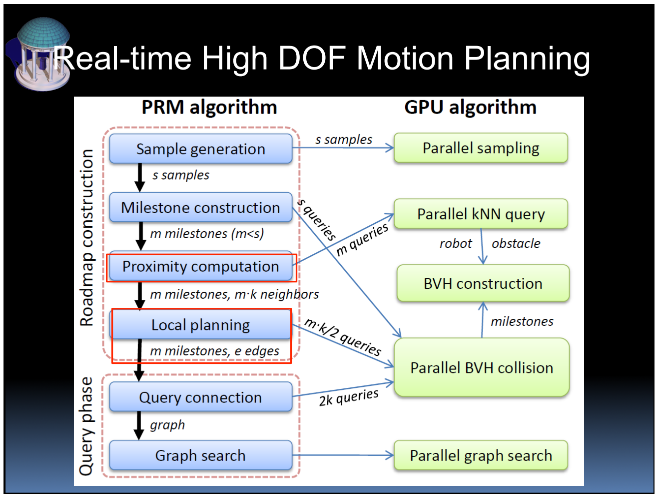
92k tris, 38ms collision

146k tris, 74ms collision



Results & Application

- Ported to NVIDIA GeForce 480 desktop GPU
  - 2.5 – 3X improvement over NVIDIA GeForce 285
  - Resulting package (gProximity) is available on the WWW
  - Used for real-time high DOF motion planning (gPlanner)



Real-time High DOF Motion Planning

PRM algorithm

GPU algorithm

Roadmap construction

Sample generation

s samples

Milestone construction

m milestones (m<s)

Proximity computation

m milestones, m·k neighbors

Local planning

m milestones, e edges

Query phase

Query connection

graph

Graph search

s samples

s queries

m queries

m·k/2 queries

2k queries

Parallel sampling

Parallel kNN query

robot

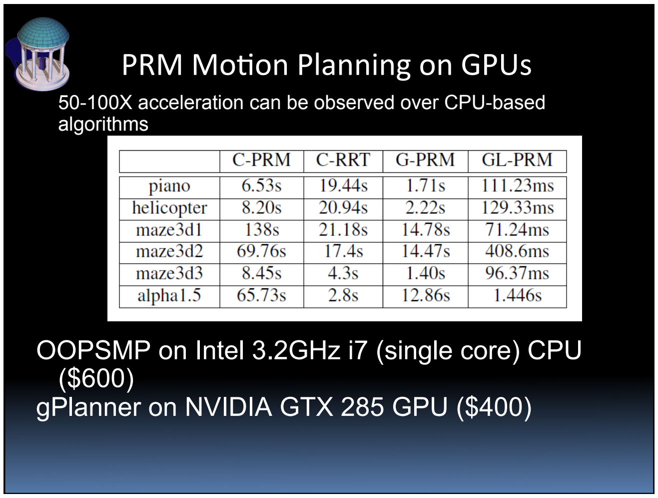
obstacle

BVH construction

milestones

Parallel BVH collision

Parallel graph search



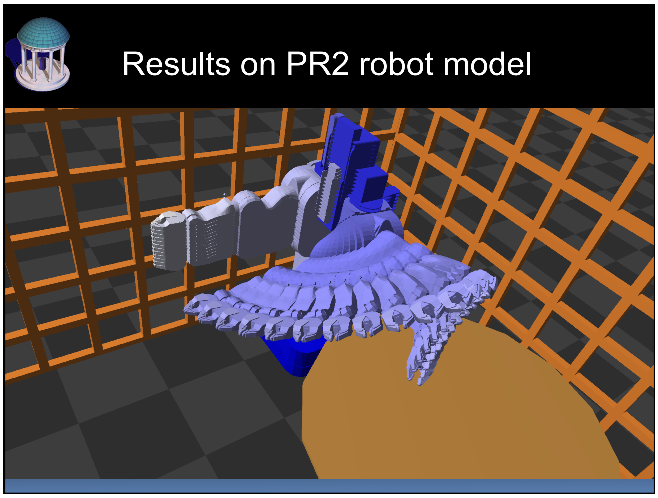
PRM Motion Planning on GPUs

50-100X acceleration can be observed over CPU-based algorithms

	C-PRM	C-RRT	G-PRM	GL-PRM
piano	6.53s	19.44s	1.71s	111.23ms
helicopter	8.20s	20.94s	2.22s	129.33ms
maze3d1	138s	21.18s	14.78s	71.24ms
maze3d2	69.76s	17.4s	14.47s	408.6ms
maze3d3	8.45s	4.3s	1.40s	96.37ms
alpha1.5	65.73s	2.8s	12.86s	1.446s

OOPSMP on Intel 3.2GHz i7 (single core) CPU ($600)

gPlanner on NVIDIA GTX 285 GPU ($400)



Results on PR2 robot model

Conclusions

- Collision and proximity queries
  - Deformable models
  - FEM and volumetric meshes
  - Penetration depth computation
- Parallel GPU-based algorithms
- Application to real-time motion planning

Future Work

- Need faster algorithms
- Integration with dynamics and FEM simulation packages
- Real-time planning on physical robots
- Parallelism and scalability?

Request to the Community

- Please take the effort to make your source code available

Acknowledgments

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  - NSF
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  - NVIDIA
  - Intel
  - Willow Garage
  - Models courtesy of Disney, Kineo CAM, BMW, LS-DYNA

Thanks!