A Benchmarking Suite for 6-DOF Real Time Collision Response Algorithms

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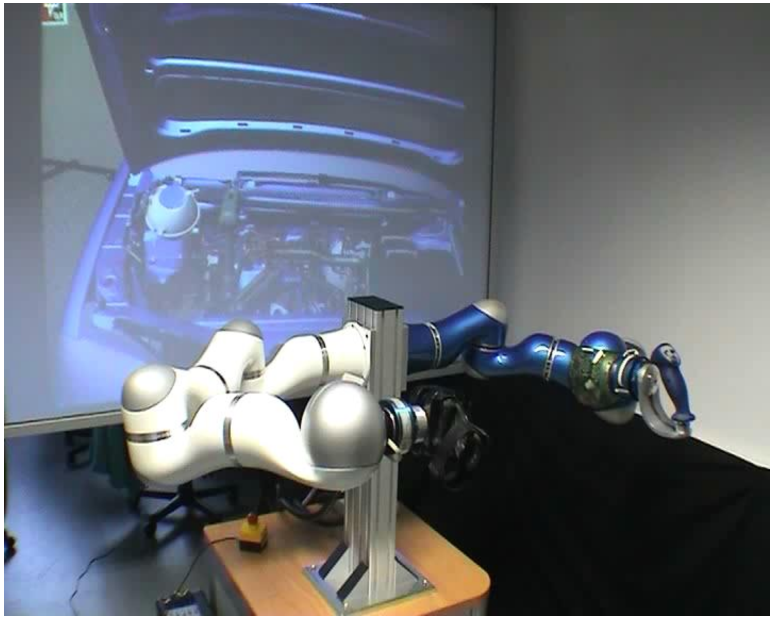
Motivation for Collision Detection



- Make virtual environments more realistic
- Basic component of video games, robotic, medical applications

Motivation for Coll.-Det. Benchmark

- Many collision detection libraries exist
  - Different data structures and/or different penetration measures
  - Difficult to compare
- Human perception is very sensitive with forces [Kim et al. 2002]
- Visual and tactical sensations are treated together in a single attentional mechanism ⇒ mismatch can affect suspension of disbelief [Spence & Driver 2000]
- Need stable and continuous forces and torques, even in extreme situations (high impact velocities or large contact areas)
- Force-feedback requires a constant update rate of 1000 Hz
  ⇒ collision detection must be very fast

Previous Work

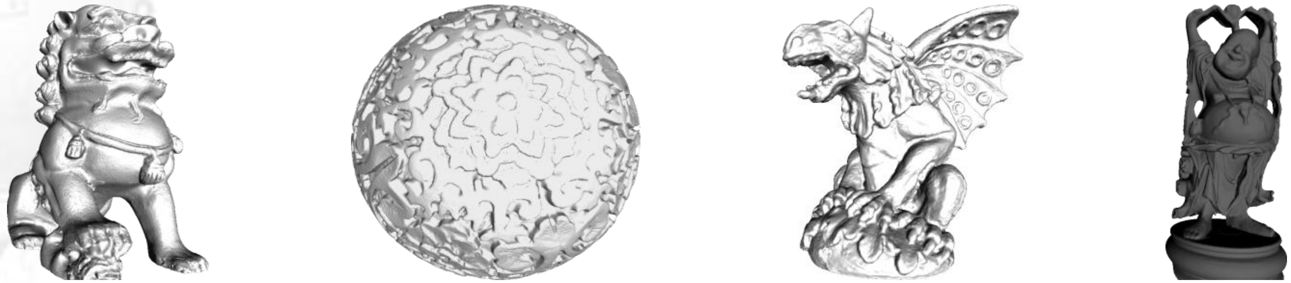
- Collision detection within context of motion planning for rigid and articulated robots in 3D workspace [Caselli et al. 2002]
  - Not of general utility and restricted to fixed set of scenarios
- 3-DOF point-based benchmark [Cao 2006]
  - Attached collision detection libraries to emulated 3-DOF point based haptic device
  - Only suitable for haptic algorithms
- Ground truth data set for haptic rendering [Ruffaldi et al. 2006]
  - Only single point of contact
- Benchmarking suite for collision detection algorithm [Trenkel et al. 2007]
  - Only distance, no comparison of expected and computed response

Contribution

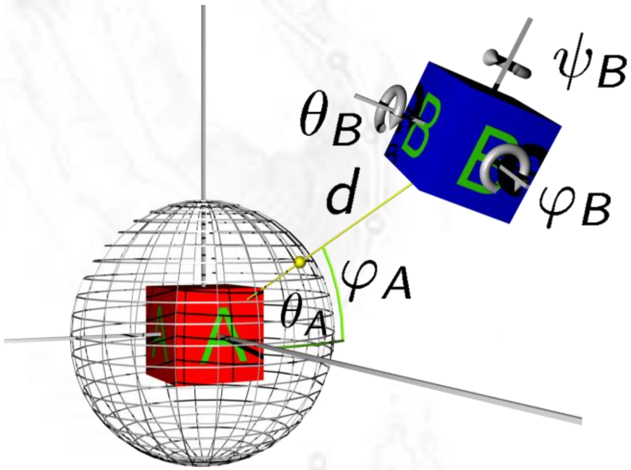
- Our Benchmarking Suite:
  1. Performance benchmark for collision detection algorithms
  2. Evaluation methodology for force and torque quality
     - Analyzes magnitude & direction values with respect to contact models
     - Noise in signals
- Evaluation
  - Compare two rather different collision detection algorithms

Part 1: Performance Benchmark

- Cover a wide variety of different, highly detailed objects e.g.:



- Move objects in vast number of different configurations and perform a collision detection test

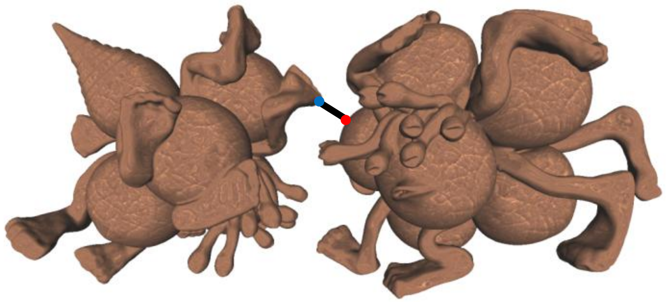


- One configuration consists of 6 parameters:
  - Translation of object B in the coordinate system of object A, given by d, φ_A, θ_A
  - Rotation of object B, given by $\varphi_B, \theta_B, \psi_B$

Performance Benchmark scenarios

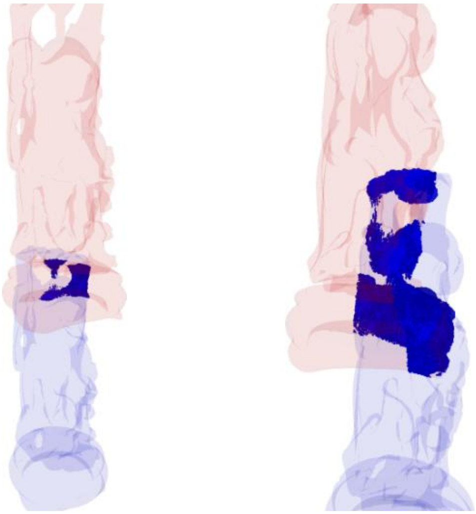
Scenario I

- Situations where objects are in close proximity, but not touching



Scenario II

- Situations where two objects intersect (from light to heavy interpenetration)



Goal:

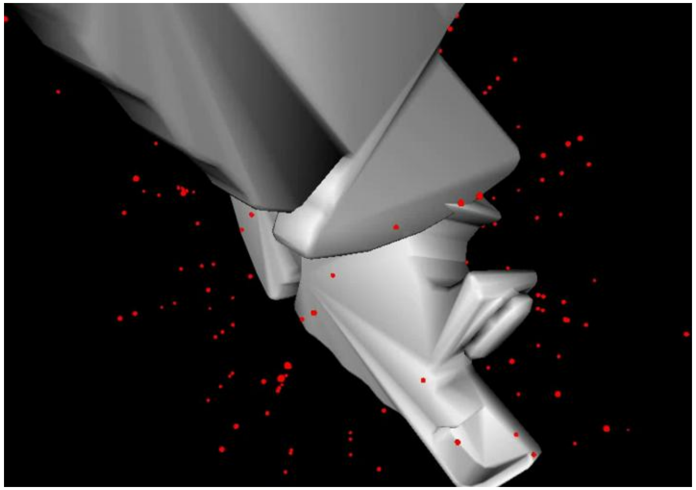
- Max and avg collision detection time
  - Sample configuration space densely

Scenario I

- Scenario I (no intersection)
  - Keep distance d fixed
  - $\Delta\varphi_A = \Delta\theta_A = 15^\circ$ and
    $\Delta\varphi_B = \Delta\theta_B = \Delta\psi_B = 15^\circ$
  - Generate 2M sample configurations for each distance
  - Compute sample configurations for distance from 0% up to 30% of object size (1% steps)

Scenario II

- Scenario II (intersection)
  - Keep intersection volume fixed
  - $\Delta\varphi_A = \Delta\theta_A = 15^\circ$ and $\Delta\varphi_B = \Delta\theta_B = \Delta\psi_B = 30^\circ$
  - For every intersection volume: 270K sample configurations
  - Sample configurations for intersection volume from 0% up to 10% of the total fixed object volume (1% steps)
- Used PC cluster with 25 cluster nodes, each with 4 Intel Xeon CPUs with 16GB of RAM
- 5 600 CPU days = 86 objects



Benchmarking procedure

Main steps:

1. Load the set of configurations for one object
2. For each object-object distance/intersection volume, start timing, set the transformation matrix of the moving object and perform a collision test
3. Get a max and avg collision detection time

- Overall we performed 65 million different collision detection tests with one collision library

Part 2: Quality Benchmark

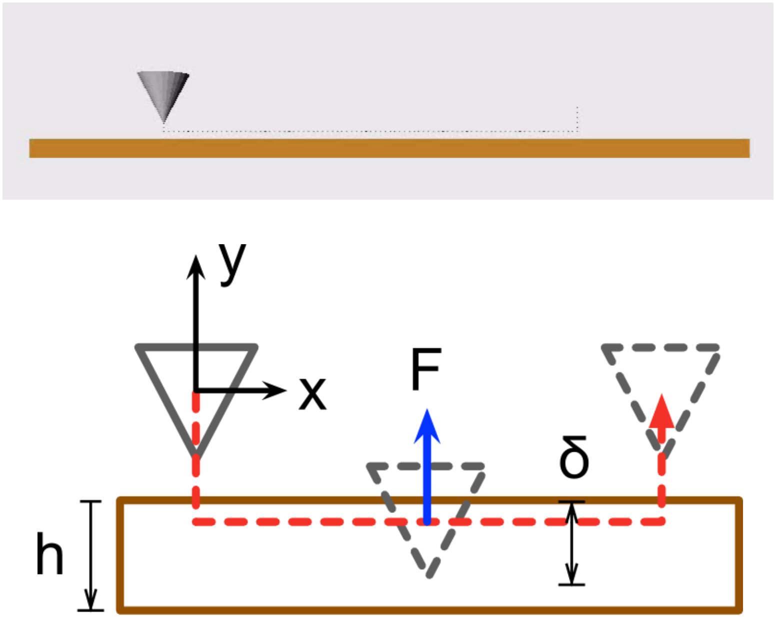
Scenarios in this benchmark should meet two requirements:

- Simple enough so that it is possible to provide an analytical model
- Suitable abstraction of the most common contact configurations in force feedback or physically-based simulations

Quality Scenario I

Reasons for this scenario:

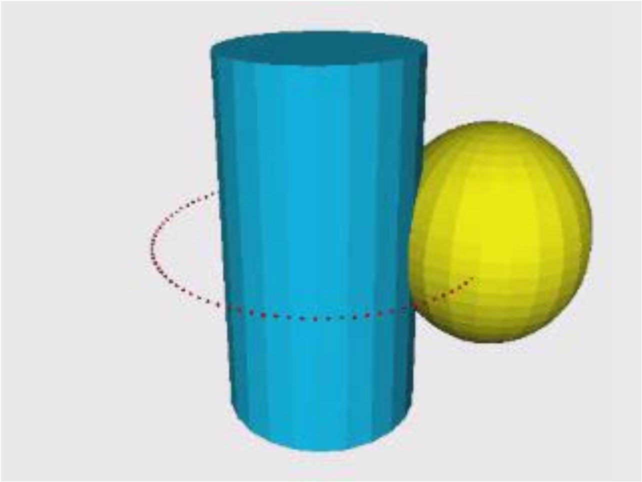
- Evaluation of behavior with flat surfaces or sharp corners
- Evaluates how algorithms handle the *tunneling effect* (h → 0)



Analytical (ideal) model:

- Expected direction of F: +y; no torques
- F = const, while cone slides on the block

Quality Scenario II

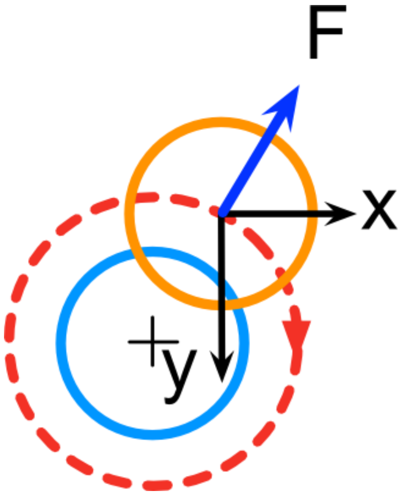


Reasons for this scenario:

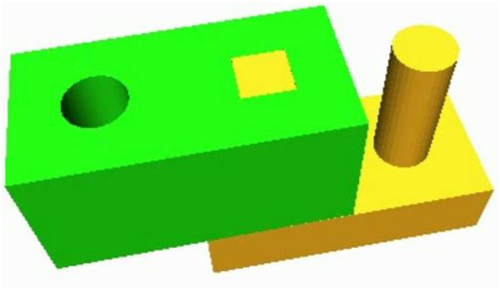
- Evaluation of behavior with smooth rounded surfaces

Analytical (ideal) model

- Expected direction of F: from cylinder center to sphere center; no torques
- |F| = const, while sphere revolves around cylinder



Quality Scenario III

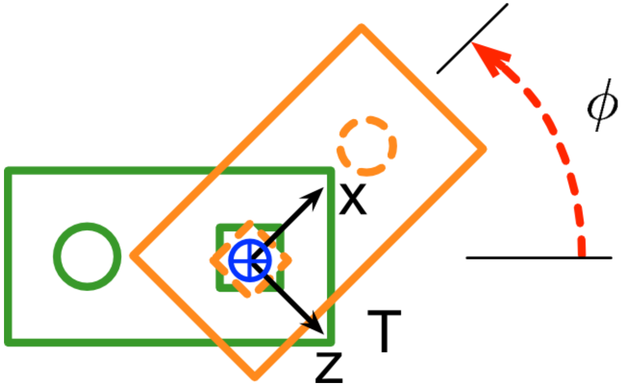


Reasons for this scenario:

- Evaluation of behavior with large contact areas

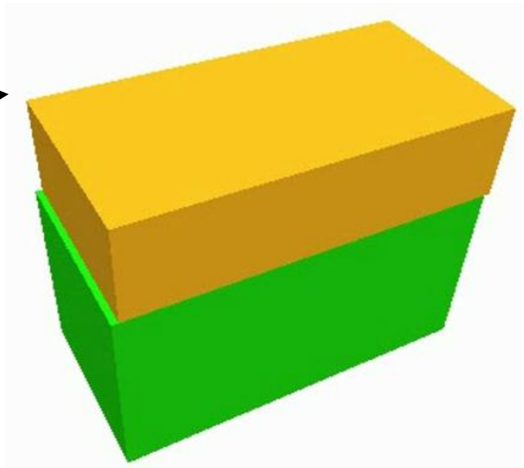
Analytical (ideal) model

- Expected direction of T: +z; no forces
- |T| should increase as ϕ increases



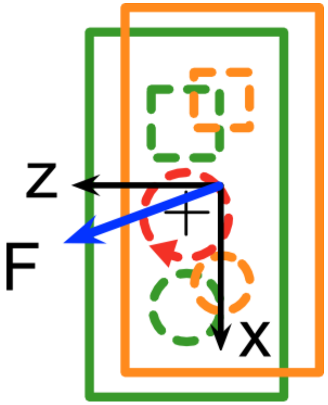
Quality Scenario IV

pins object →



Reasons for this scenario:

- Evaluation of behavior with small displacements around a configuration in which two concave objects are in large surface contact



Analytical (ideal) model

- Expected forces and torques are those that bring *pins* object towards the central axis (push *pins* object back to resting configuration)
  - Expected direction of F: sinusoid in XZ plane

Benchmarking procedure

Main steps:

1. Measured (m) and recorded values in each time stamp k: forces $\mathbf{F}_k^{\mathrm{m}}$, torques $\mathbf{T}_k^{\mathrm{m}}$, penalty values q_k^{m} (volume, penetration), computation time t_k
2. Computation of ideal (i) force $\mathbf{F}_k^{\mathrm{i}}$ and torque $\mathbf{T}_k^{\mathrm{i}}$ (volume based and penetration based model)
3. Compare ideal (i) and measured (m) values

Proposed quality measures

1. Deviation of magnitude of measured (m) forces from ideal (i) forces (RMSE)

$$\sigma_F = \frac{1}{N}\sqrt{\sum_{k=1}^{N} \left(\|\hat{\mathbf{F}}_k^{\mathrm{i}}\| - \|\hat{\mathbf{F}}_k^{\mathrm{m}}\| \right)^2}, \quad \hat{\mathbf{F}} = \frac{\mathbf{F}}{\|\mathbf{F}\|_{\max}}$$

where N being total number of time stamps

2. Deviation for the direction

$$\gamma_F = \frac{1}{N}\sum_{k=1}^{N} \arccos \frac{\mathbf{F}_k^{\mathrm{i}} \mathbf{F}_k^{\mathrm{m}}}{\|\mathbf{F}_k^{\mathrm{i}}\| \cdot \|\mathbf{F}_k^{\mathrm{m}}\|}$$

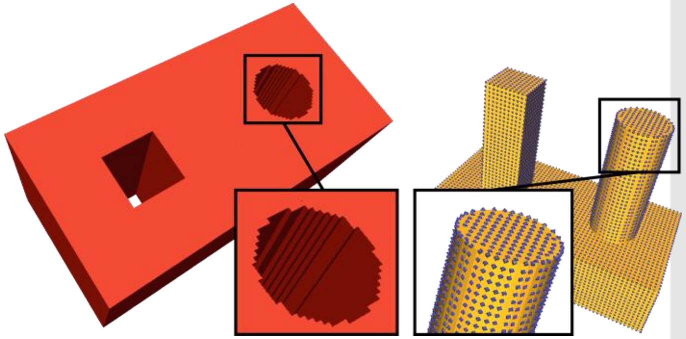
3. Similarly for torques
4. Amount of noise by short time Fourier transform

Evaluated Algorithms

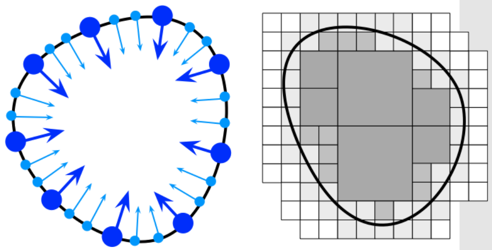
- Quite different algorithms Voxmap-Pointshell (VPS) and Inner Sphere Tree (IST)
- Both Penalty based haptic rendering method

	IST	**VPS**
Penalty value	Intersection volume	Penetration depth
Data structure	Sphere packing	Voxmap & Pointshell

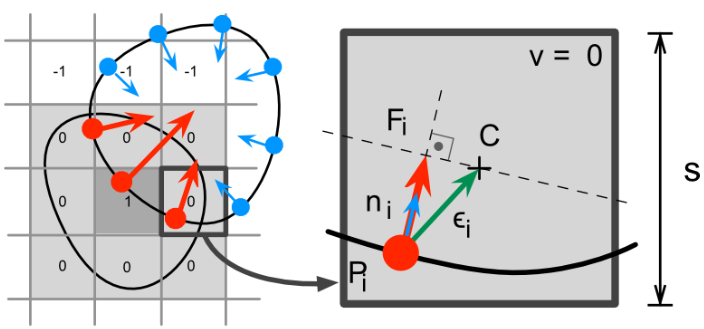
Voxmap-Pointshell algorithm



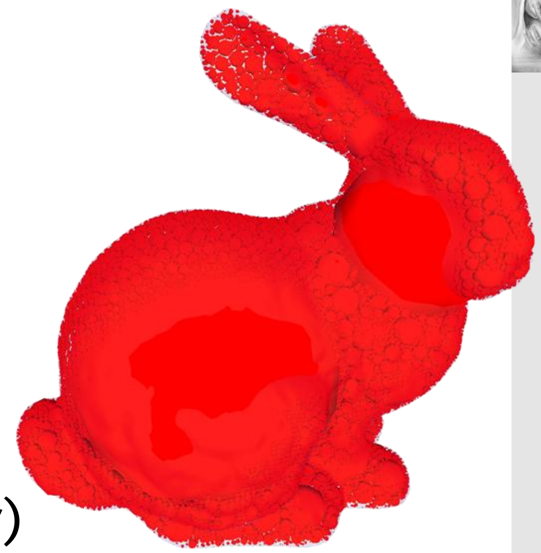
- Two types of data structure
  (generated offline)
- Voxmap:
  - 3D grid: each voxel stores discrete distance value $v \in \mathbb{Z}$ to surface
- Pointshell:
  - Set of points uniformly distributed on the surface



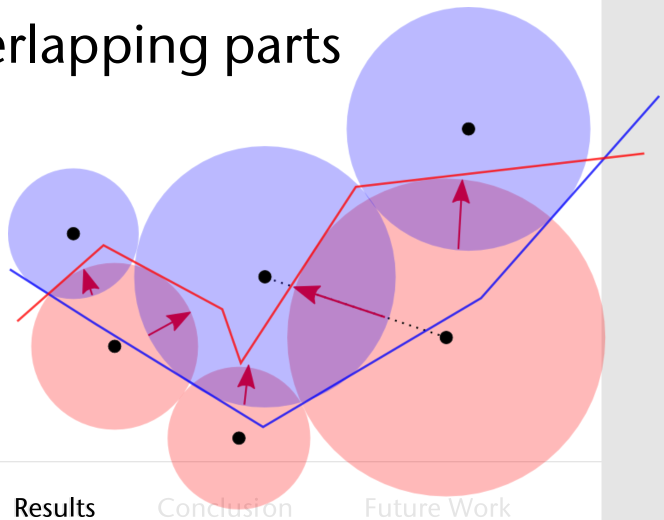
- Likely colliding points are checked for collision ($v \geq 0$)
- F = normal vectors $\mathbf{n}_i$ of colliding points P_i are summed
- Penalty value = penetrated distance



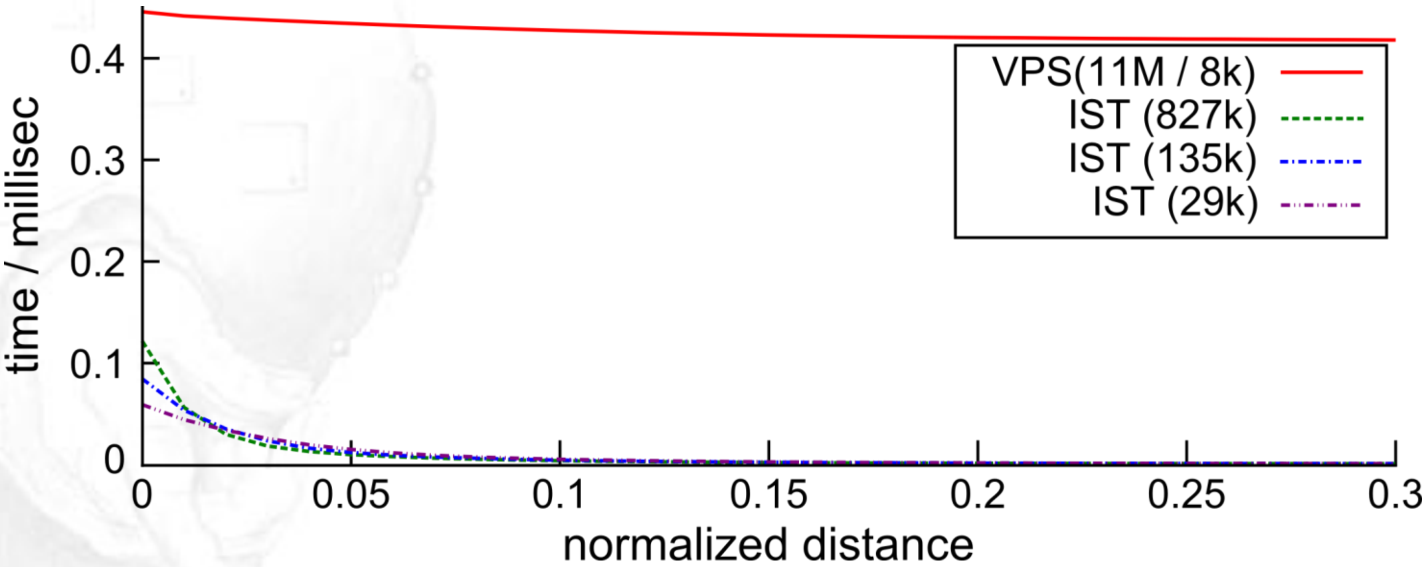
Inner Sphere Tree algorithm

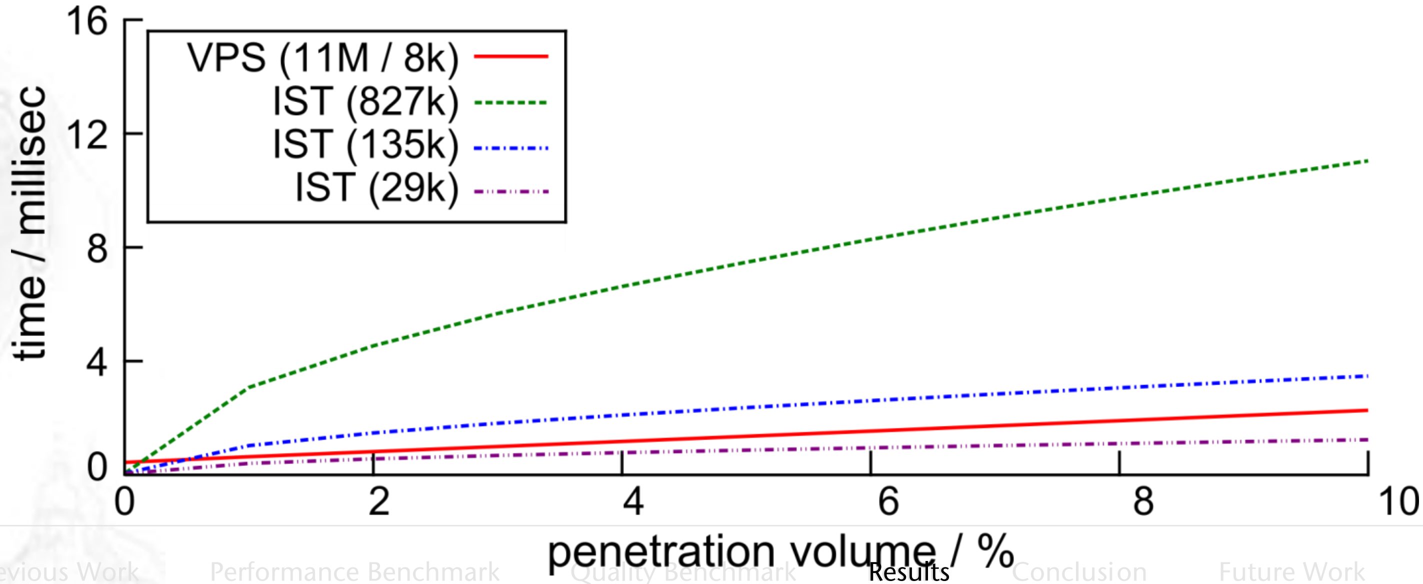


- Provides hierarchical bounding volumes from *inside* of an object
- Fill interior of model with non overlapping spheres (approximate object's volume closely)
- Independent of geometry complexity (only depend on approximation error)
- Penalty value = penetration volume computation ⟶ corresponds to water displacement of overlapping parts (physically motivated)

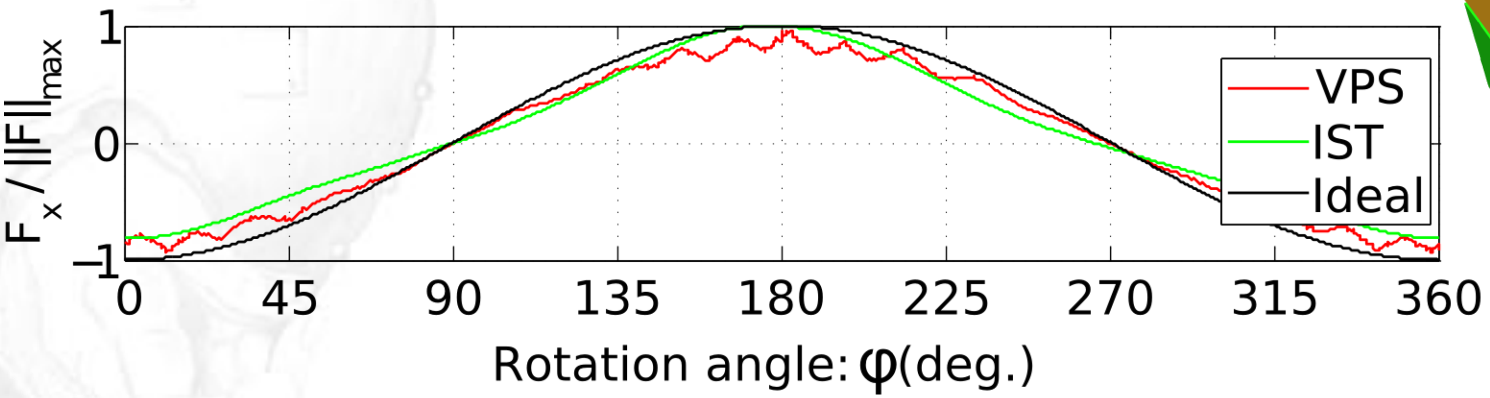


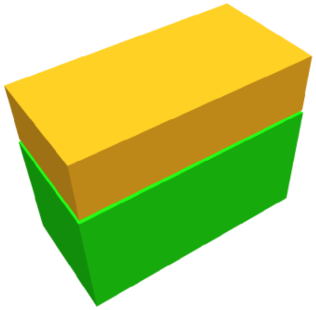
Results: Performance Benchmark

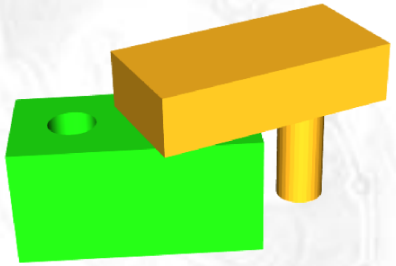


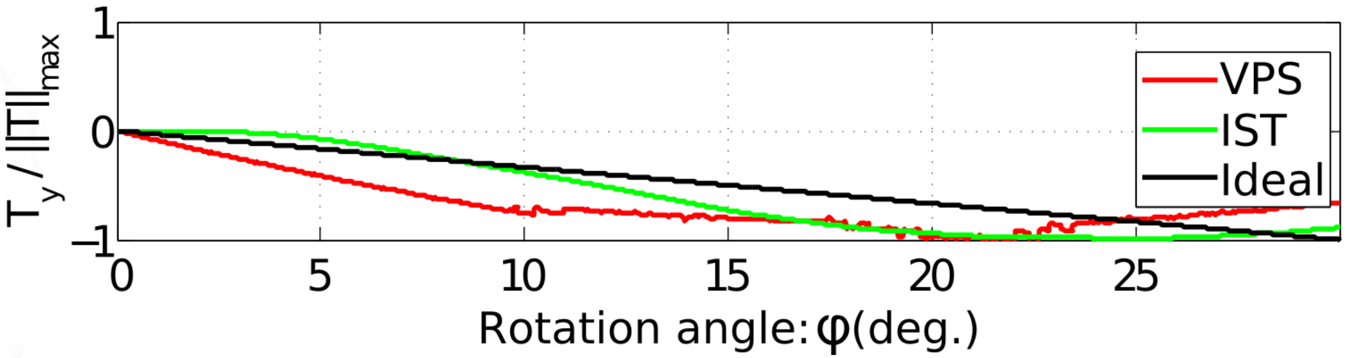


Results: Quality Benchmark

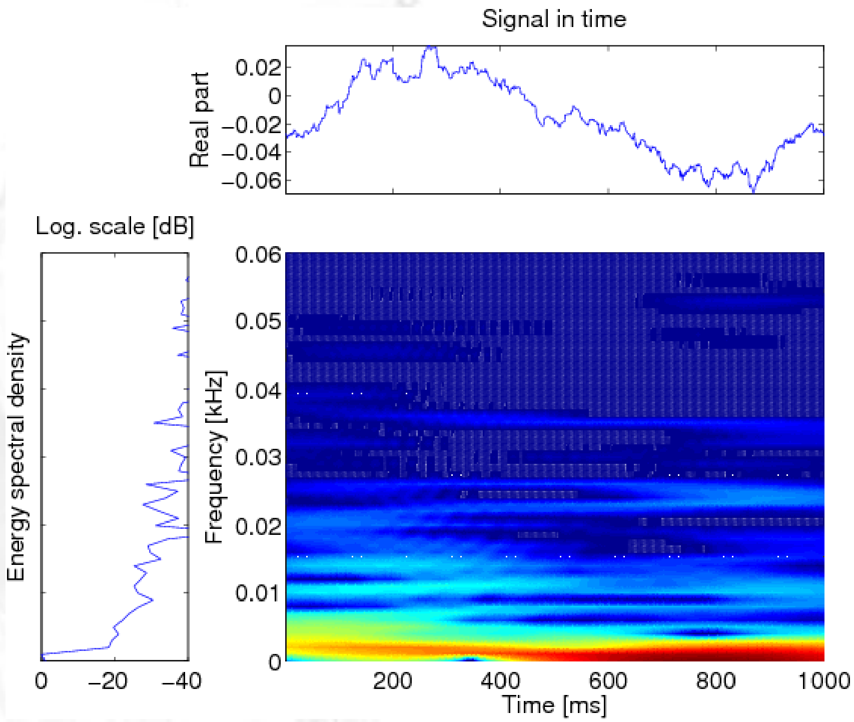




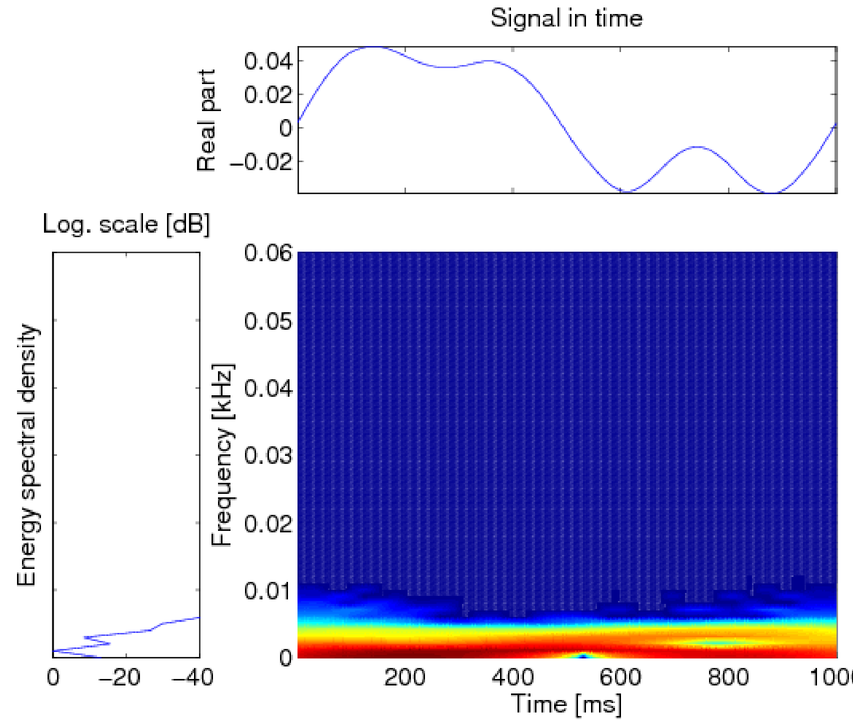




Results: Quality Benchmark



VPS



IST

- Color code intensity of frequency (dark blue represents intensity of zero)

Conclusions

- Easy to benchmark quite different collision detection algorithms
- Benchmark both performance and quality
- Cover wide range of scenarios
- Benchmark and configurations published as open source (soon)

  (http://cg.in.tu-clausthal.de/research/colldet_benchmark/index. shtml)

Future Work

- Weighting of different measurements → ranking of algorithms
- Standardized benchmarking suite for deformable objects is still missing
- Benchmarking of more algorithms

Acknowledgments

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