Sphere-tree based collision detection for constraint-based 6-DOF haptic rendering

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Outline

- Constraint-based 6-DOF haptic rendering
- Challenges of collision detection
- Sphere-tree based collision detection
- Experiment results
- Conclusions and future works

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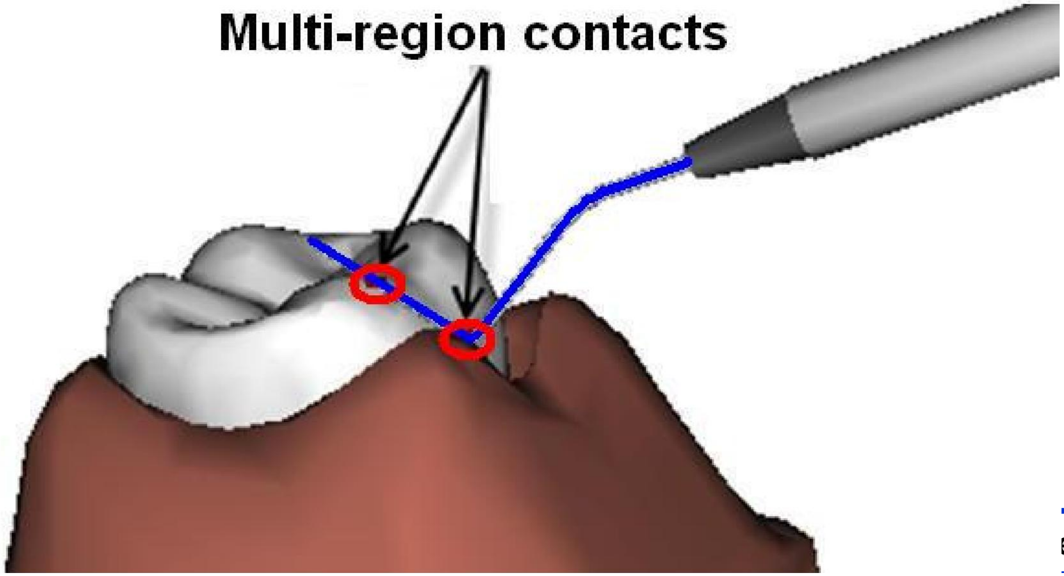
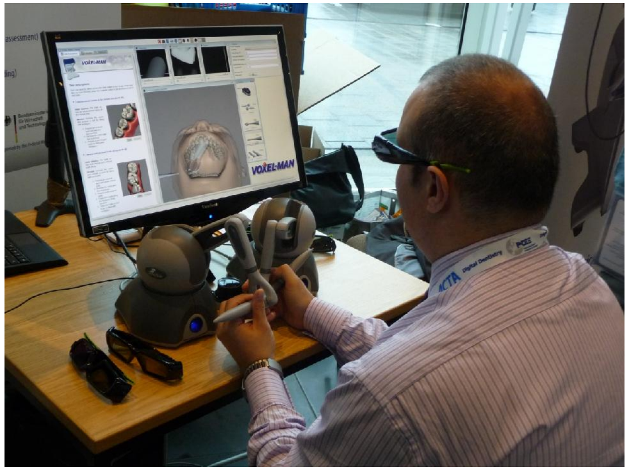
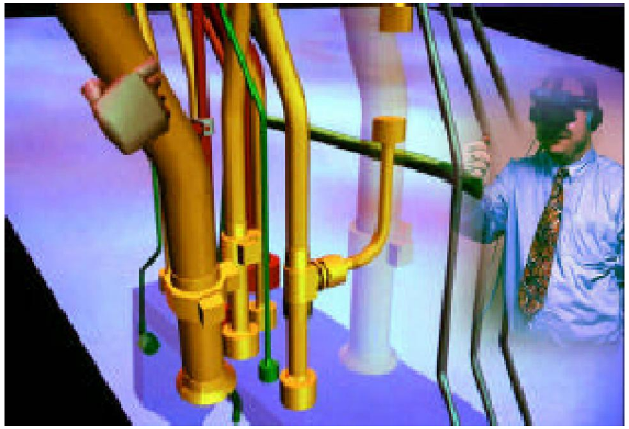
6-DOF haptic rendering

- Importance of 6-DOF haptic rendering
  - Lots of applications
  - To improve fidelity and immersion
- Requirements of 6-DOF rendering
  - Multiple-region contacts
  - Six dimensional force and torque
  - Realistic, stable, and haptic rates



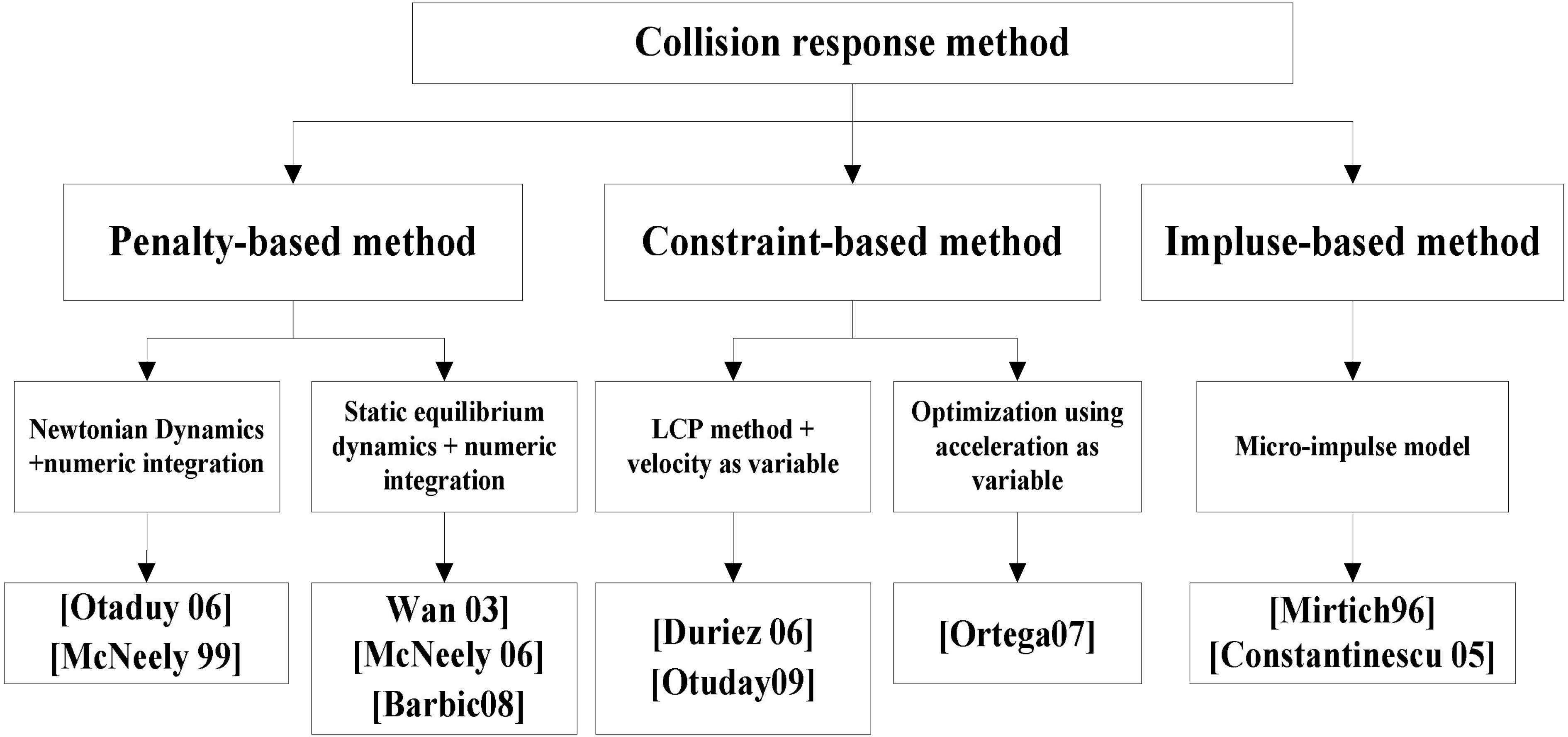


Surgery simulation

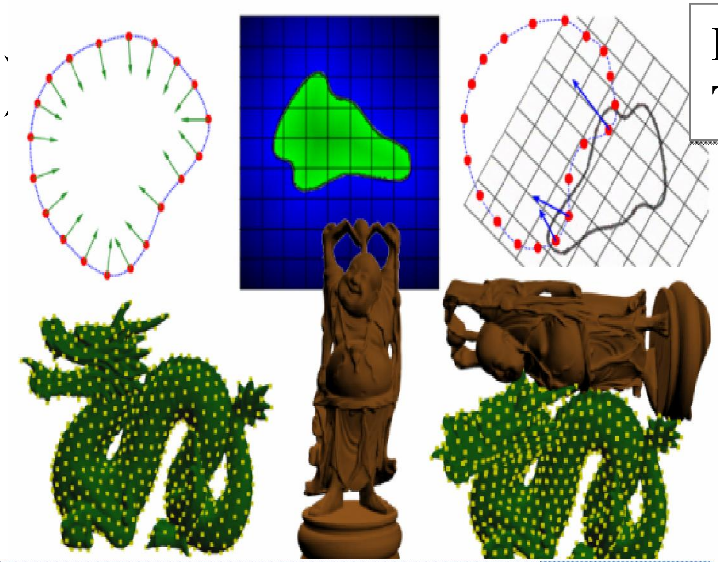


Virtual maintenance

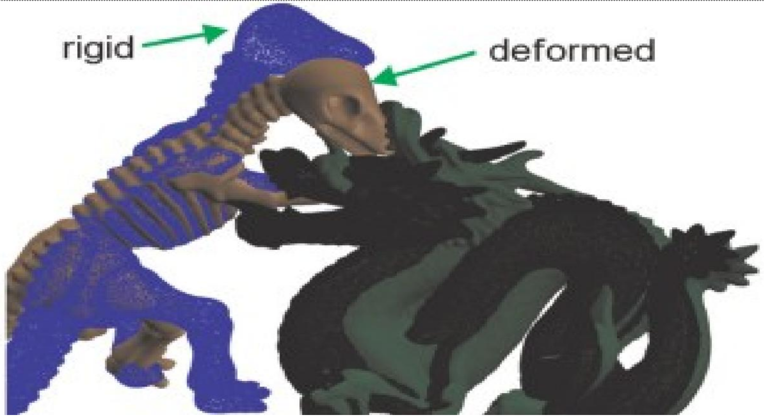
Literature review (1/5)



Literature review (2/5)



Point shell + distance field
Transaction on Haptics, 2008, Barbic & James



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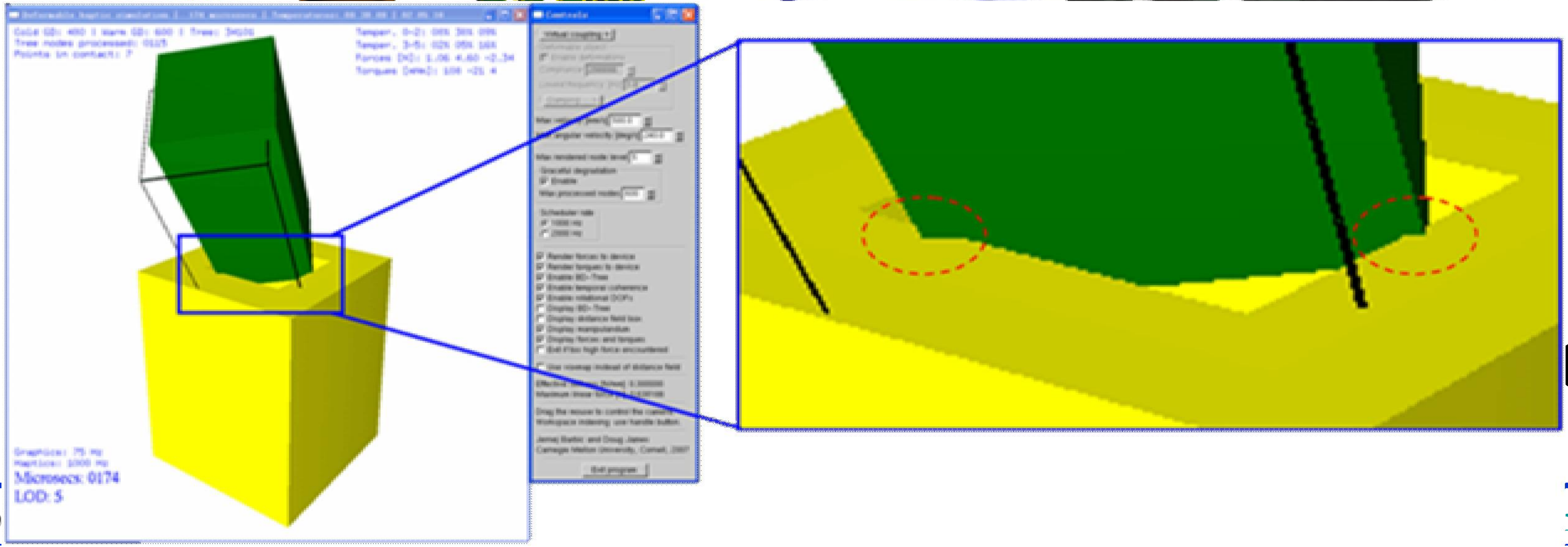

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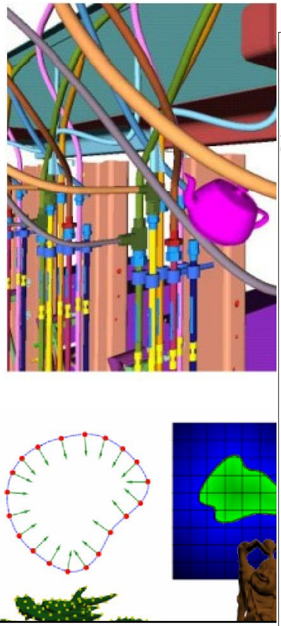
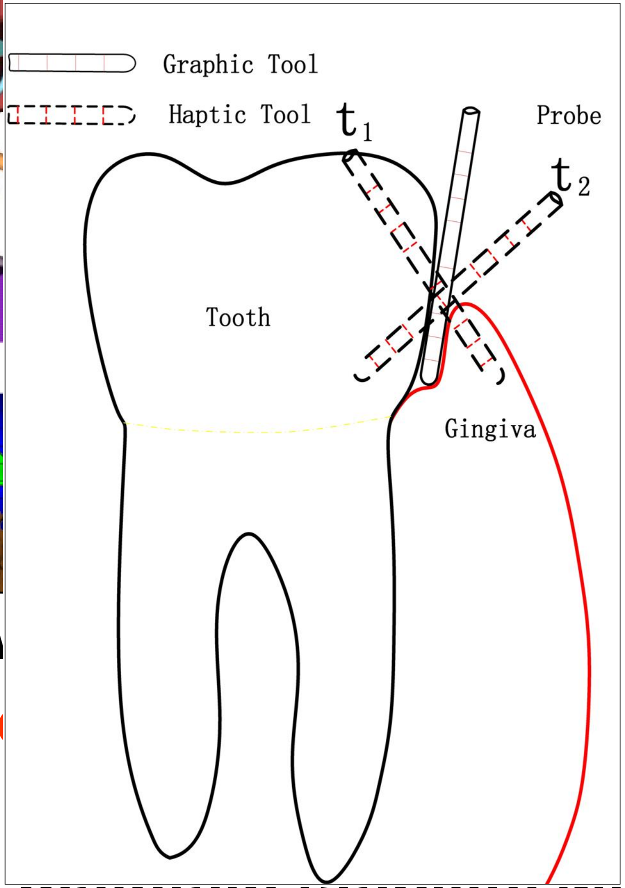
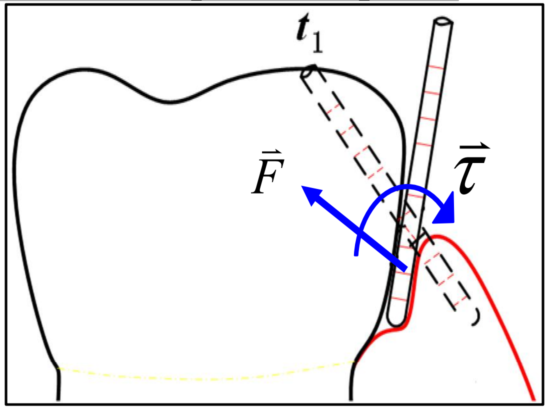
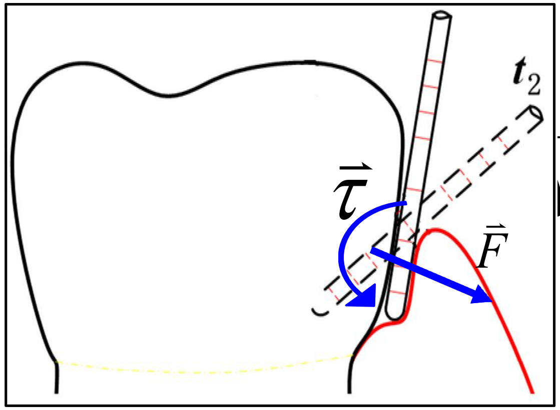
Literature review (3/5)









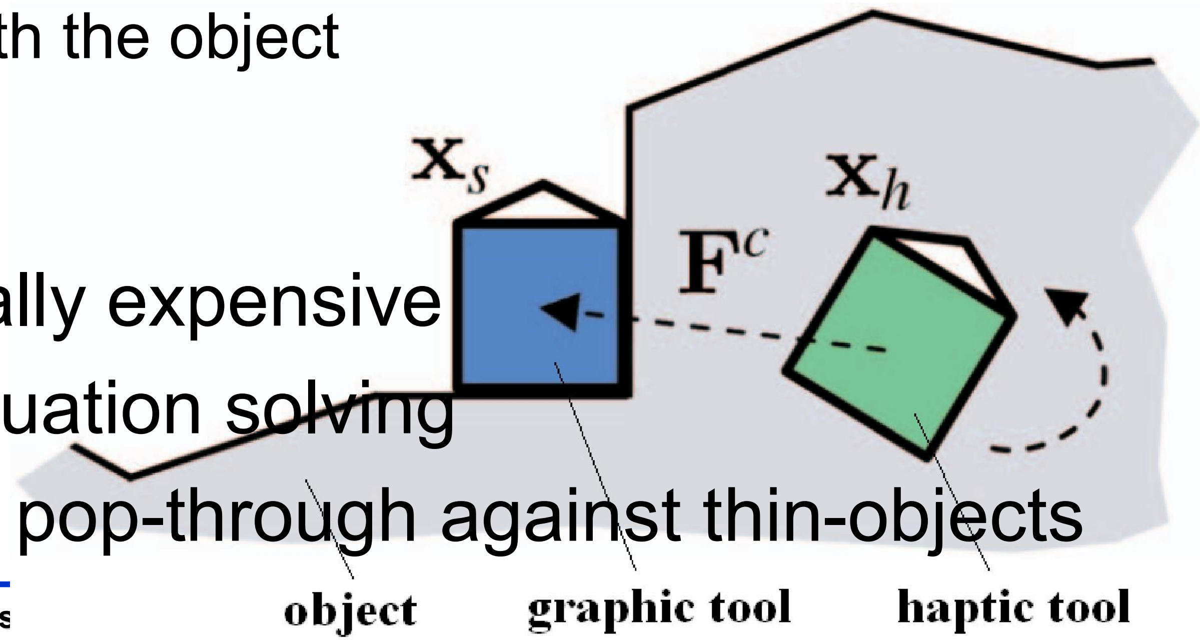
- These v… y
- But for…
- How to … orce renderi…

Contact switch→ force/torque discontinuity
→ make the haptic device unstable

Literature review (4/5)

- **6-DOF haptic rendering**
  - **Constraint-based methods:** [Duriez *et al.* 06], [Ortega *et al.* 07]
    - Constrain the graphic avatar (i.e., the graphic tool) of the moving tool (i.e., the haptic tool) to be free of penetration with the object

- **Limitation:**
  - Computationally expensive
    - Iterative equation solving
  - Can't prevent pop-through against thin-objects

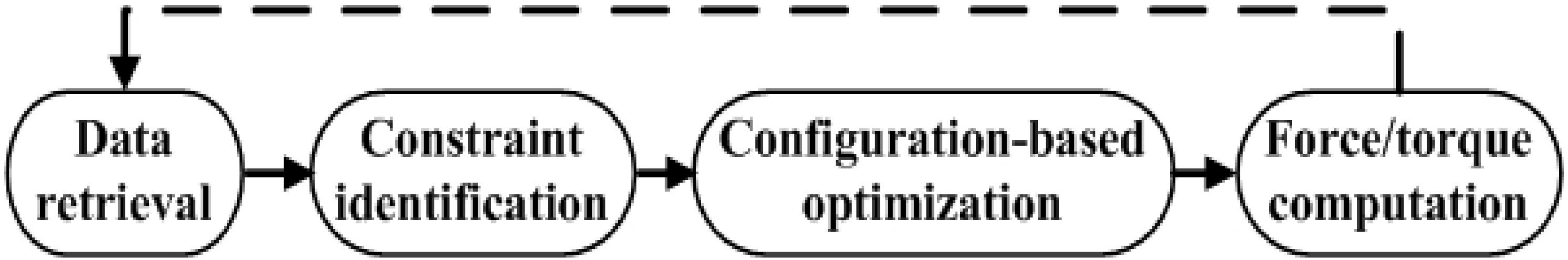


Literature review (5/5)

- **Limitations of existing methods**
  - **Need transition among multiple object models [e.g. Mendoza and O'Sullivan 05]:**
    - sphere-tree (collision detection)
    - a coarser mesh (deformation)
    - a tetrahedron model (collision response)
    - a fine mesh (graphic display)

UNC CHARLOTTE

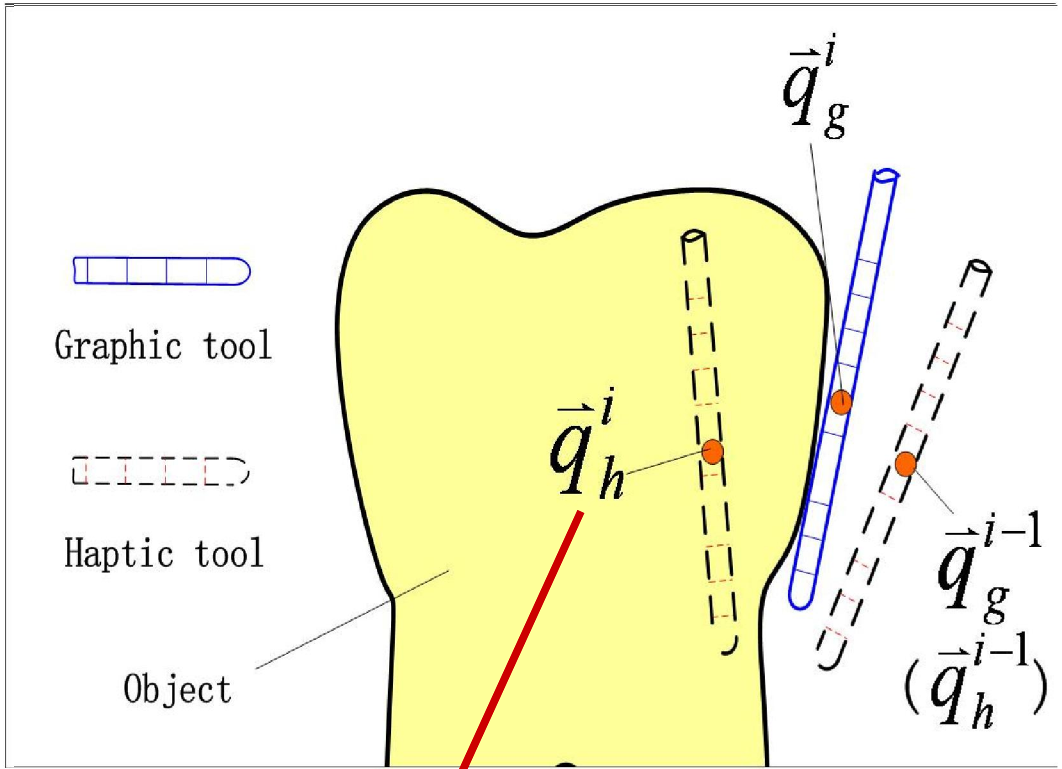
Overview of our method



- **Contributions**
  - A ***configuration-based optimization method*** to compute contact configurations of the graphic tool (i.e. the god-object)
  - A ***constraint identification method*** to detect contact switches and formulate the set of constraints for the optimization model
  - A force/torque computation model ***without using virtual coupling***, to eliminate haptic artifacts and to maintain stability

Configuration-based optimization

- **Input:**
  - **Surface and configuration of the object (e.g. the tooth)**
  - **Configuration of the *haptic tool***
- **Output:**
  - **Configuration of the *graphic tool* (Avatar of the haptic tool)**
  - **Feedback force and torque**



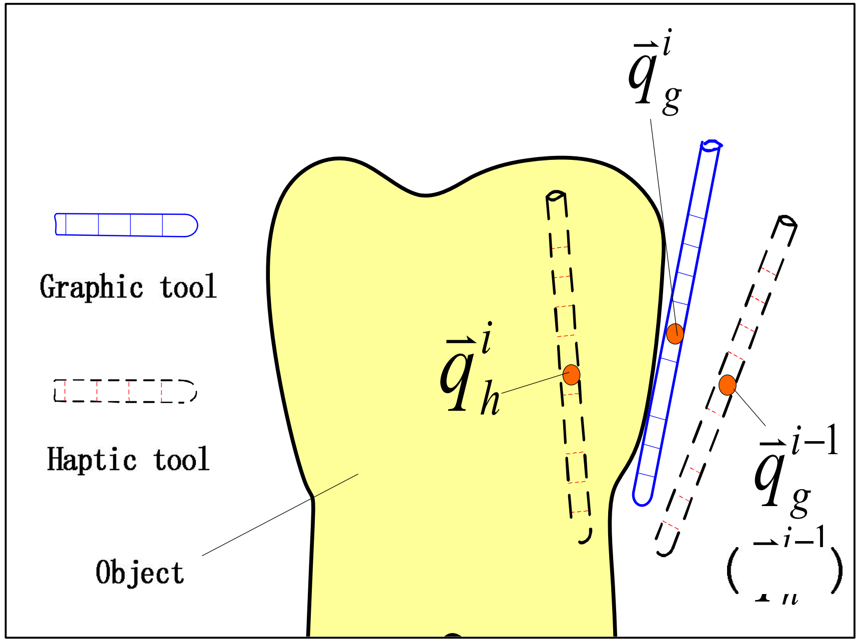
$$\begin{cases} \vec{q}_h = [x_h, y_h, z_h, \gamma_h, \beta_h, \alpha_h]^T \\ \vec{q}_g = [x_g, y_g, z_g, \gamma_g, \beta_g, \alpha_g]^T \end{cases}$$

Configuration-based optimization

- **Optimization model**
  - **Objective function**
  - **Non-penetration constraints**

$$\begin{cases} \min : f\left(\vec{q}_g^{\,i}\right) \\ Subject \quad to: \quad V_O \cap V_T = \varnothing \end{cases}$$

$$f\left(\vec{q}_g^{\,i}\right) = \frac{1}{2}\left(\vec{q}_g^{\,i} - \vec{q}_h^{\,i}\right)^T M \left(\vec{q}_g^{\,i} - \vec{q}_h^{\,i}\right)$$



- **Force/torque computation**

$$\vec{F} = K_e\left(\vec{q}_g - \vec{q}_h\right)$$

Six-dimensional non-linear optimization problem (Quadratic Programming)

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- **Challenges of collision detection**
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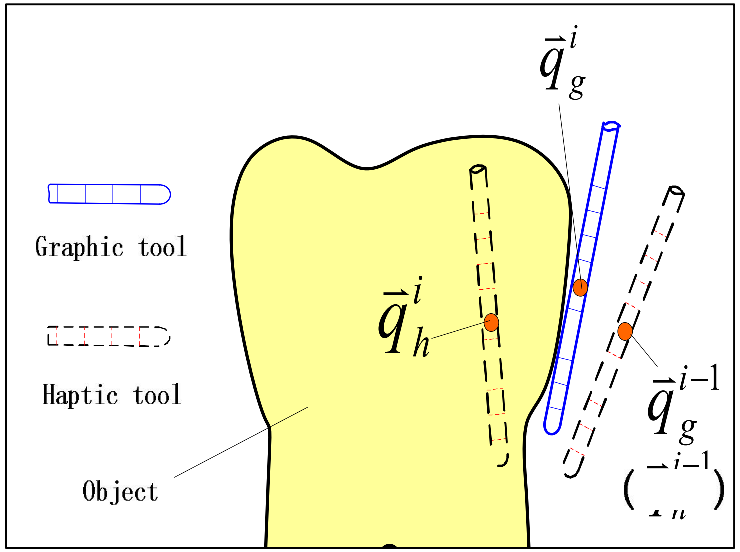
Challenge 1

- **Optimization model**
  - **Objective function**
  - **Non-penetration constraints**

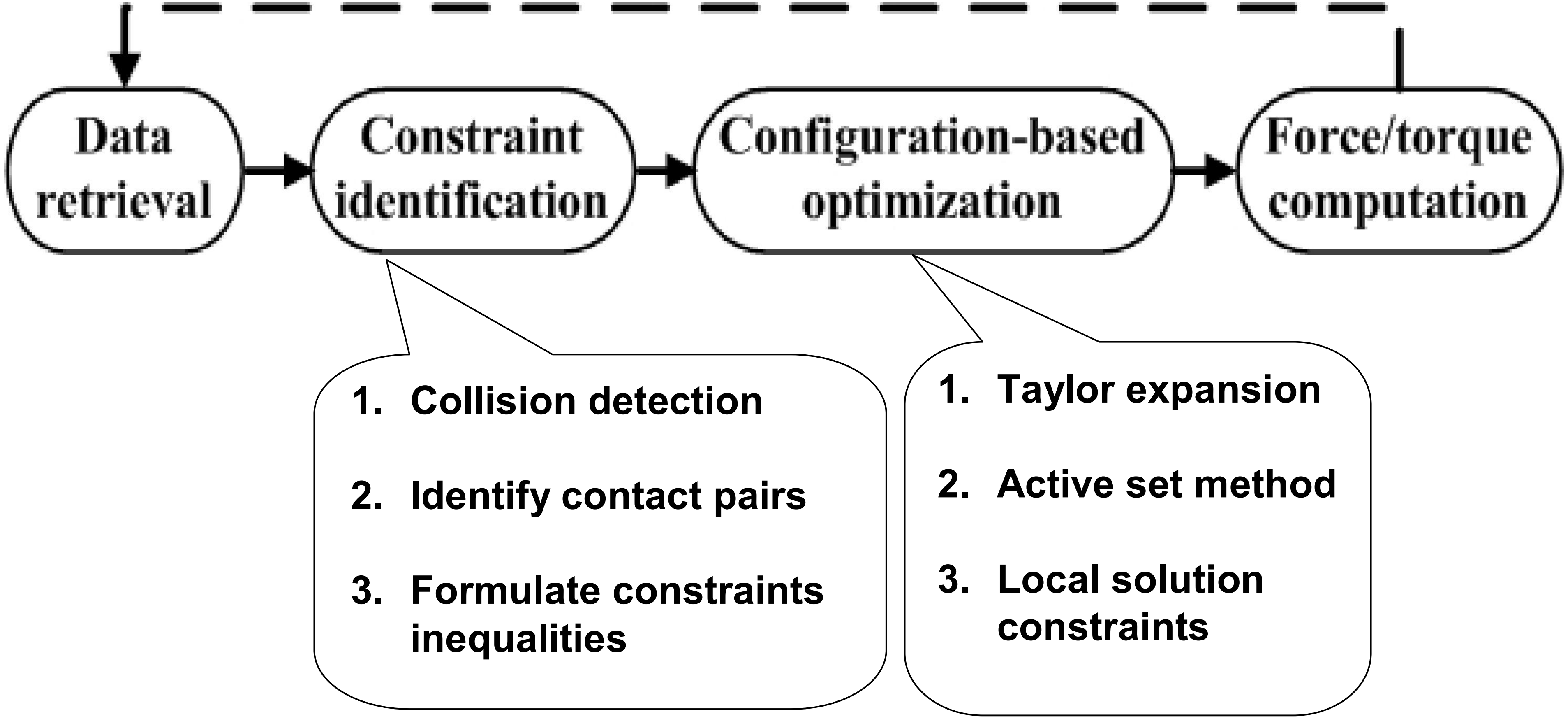
$$\begin{cases} \min : f\left(\vec{q}_g^{\,i}\right) \\ Subject \quad to: \quad V_O \cap V_T = \Phi \end{cases}$$



Challenge: Constraint identification and formulation

How to model the non-penetration constraints?

Implementation of our method



Non-penetration constraints

- **Challenge 1**
  - Variety of the contact scenarios and modeling both convex and non-convex features

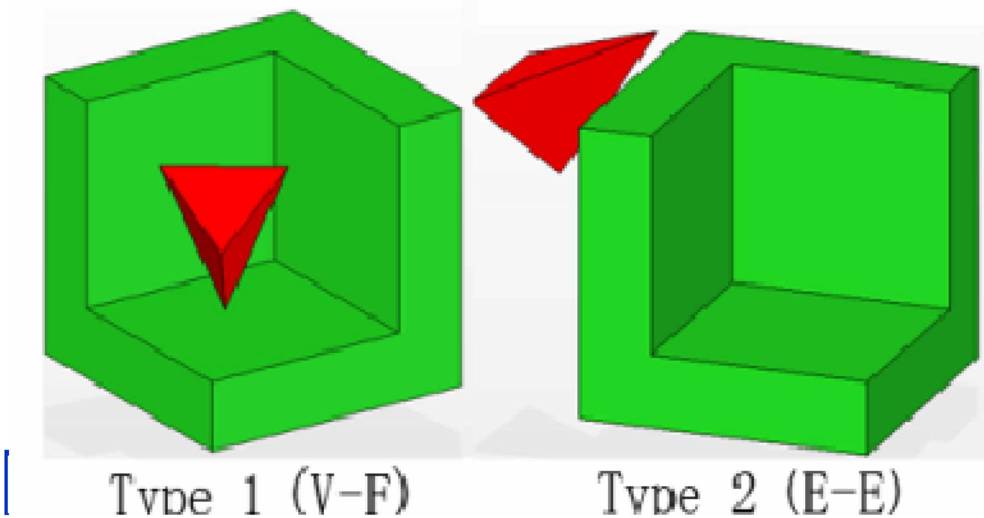
Tool \ Object	Vertex convex	Vertex concave	Edge convex	Edge concave	Triangle
Vertex (convex)	*Type 9*	Type 4	*Type 8*	Type 3	**Type 1: V-F type**
Edge (convex)	*Type 10*	-----	**Type 2: E-E type**	Type 5	Type 6
Triangle	Type 11	----	Type 12	----	Type 7

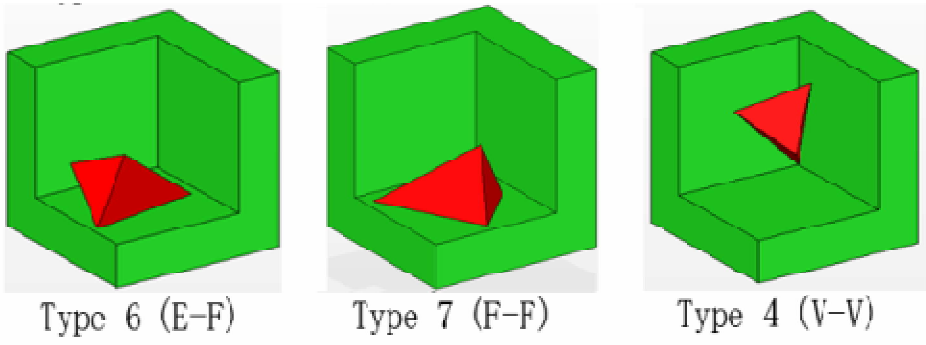
Different types of single-region contacts

Single contact region

- **Classification of contacts:**
  - Basic contacts: Type 1 (V-F), Type 2(E-E)
  - Other contacts: Combination of basic contacts
  - Degenerate contacts: Types 8-10

Basic contacts





Combined contacts

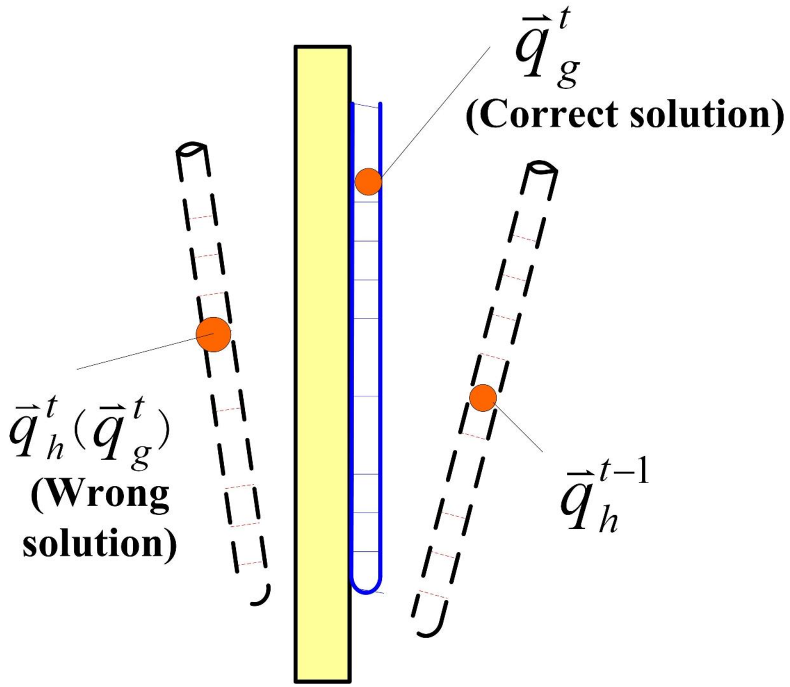
Non-penetration constraints

- Challenge 2
  - Transitions among contact states, i.e., modeling transitions among contact states during the tool's movement

- Challenge 3
  - Multiple-point contacts

Non-penetration constraints

- **Challenge 4**
  - To avoid pop-through against thin or small-sized objects



Modeling choices

- To construct non-penetration constraints between two complex-shaped objects
- Choices
  - Triangle mesh: cannot model non-penetration constraints against local region around convex features, i.e. too many different contact-pairs scenarios need to be modeled;
  - Voxel or distance field model: cannot be solved easily in an optimization process
  - Sphere-tree model: easy to approximate complex-shaped objects, and to formulate non-penetrated constraints

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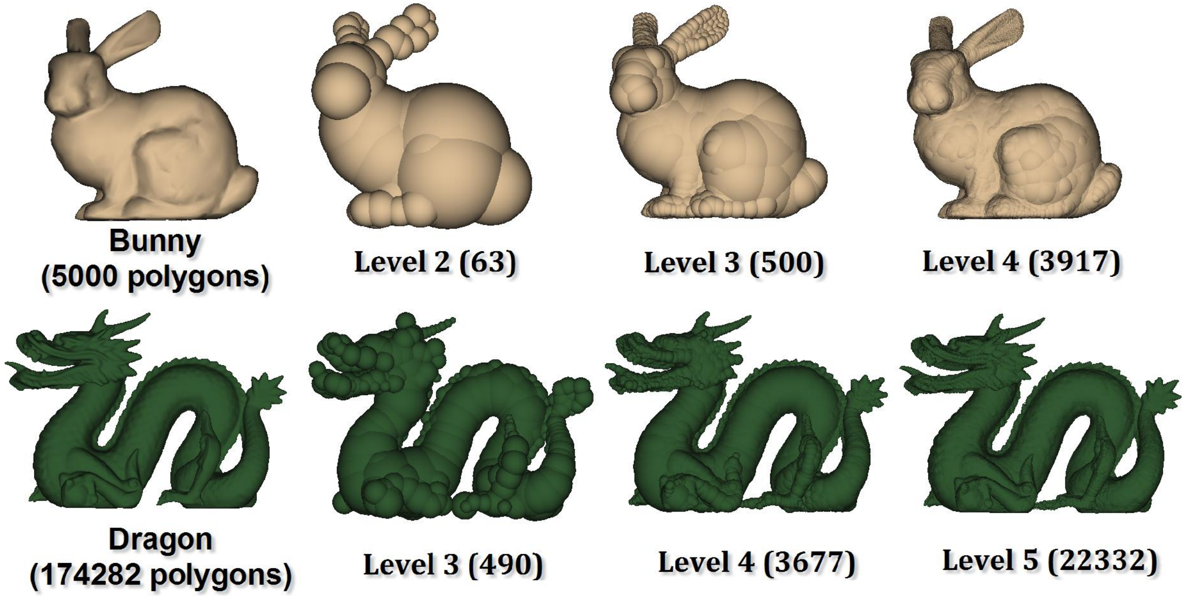
Sphere-tree model

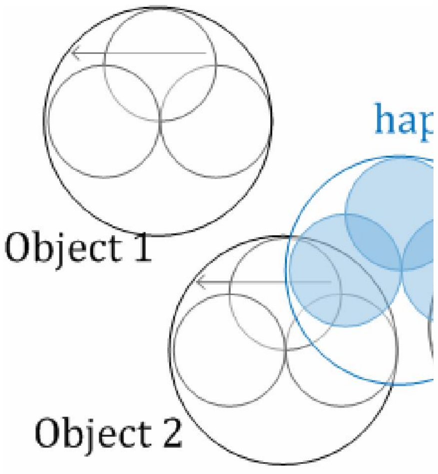
- Hubbard, medial-axis based sphere tree model
- Bradshaw's Sphere Tree Construction Tool-kit



Sphere-trees generated for a bunny and a dragon.

S-CD method

- Sphere-tree based collision detection (S-CD) method



(a) broad pl

```
input: S: array for the intersected pairs of root spheres
s1, s2 = S.GetElementByIndex(0)
while(s1&s2 are not leaf nodes)
    S.RemoveElementByIndex(0)
    S1 ← children of s1 that intersect s2
    S2 ← children of s2 that intersect s1
    for each pair (s'1,s'2), s'1 ∈ S1, s'2 ∈ S2
        if(s'1 intersect s'2)
            S.AddElementToArray((s'1, s'2))
            (s1,s2) = S.GetElementByIndex(0)
output: S: array for intersected pairs of leaf-nodes
```

S-CD method

- **Pros:**
  - Easy to implement

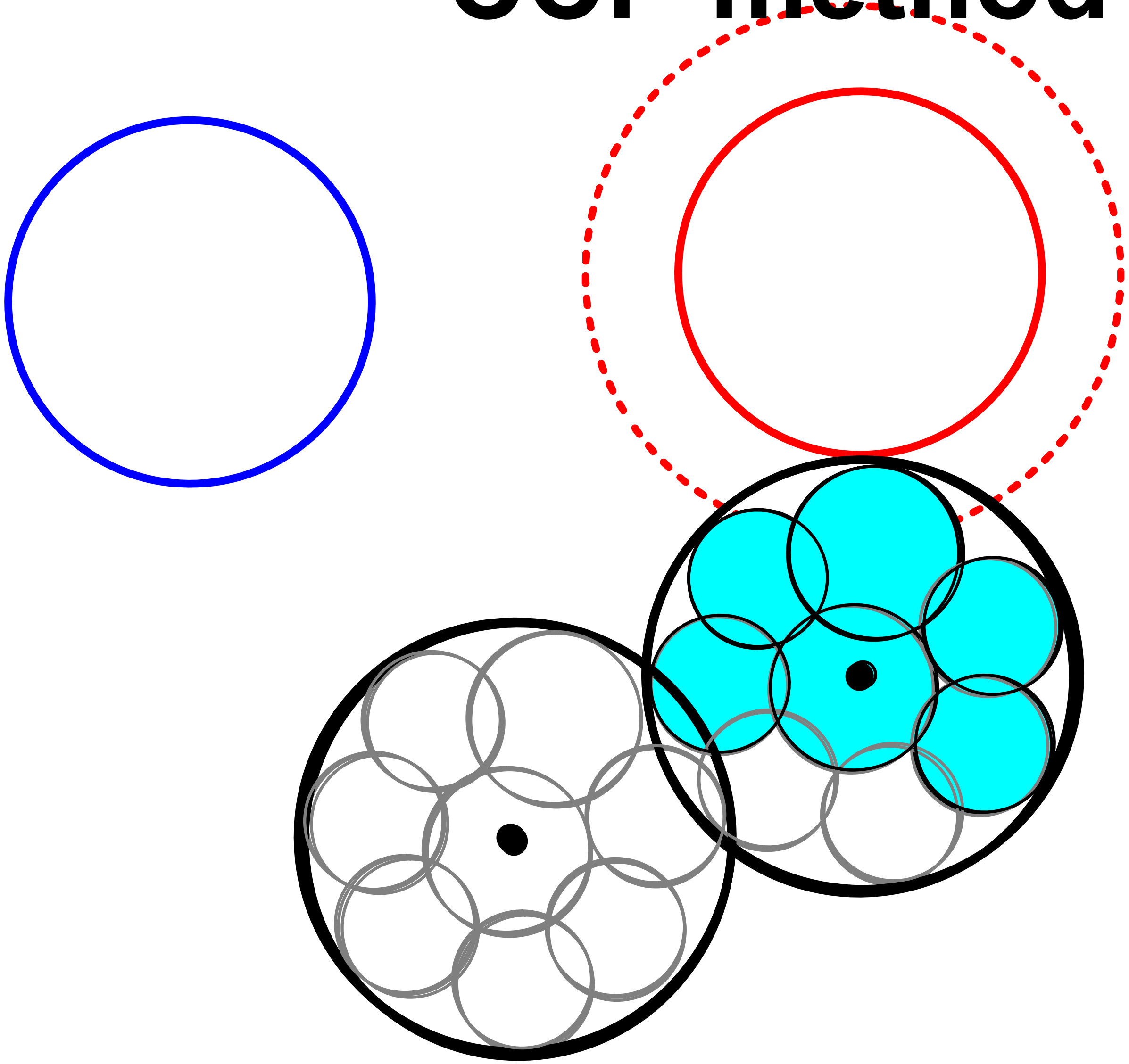
- **Cons:**
  - Update rate is lower than 1kHz when a detailed level (e.g. level 4) is used

S-CCP method

- **S-CD method**
  - **Check between the haptic tool vs. objects**

- **A Sphere-tree based *contact constraint-prediction* (S-CCP) method**
  - **Check between an enlarged graphic tool** (at previous time step) **vs. objects**
  - **Based on two observations**
    - Motion coherency of the tool
    - Delicate motion of tools such as surgical instruments

CCP method



- Grow each sphere of the graphic tool at *t*-1
- Find the pairs of intersecting spheres
- Greatly reduce the number of contact pairs

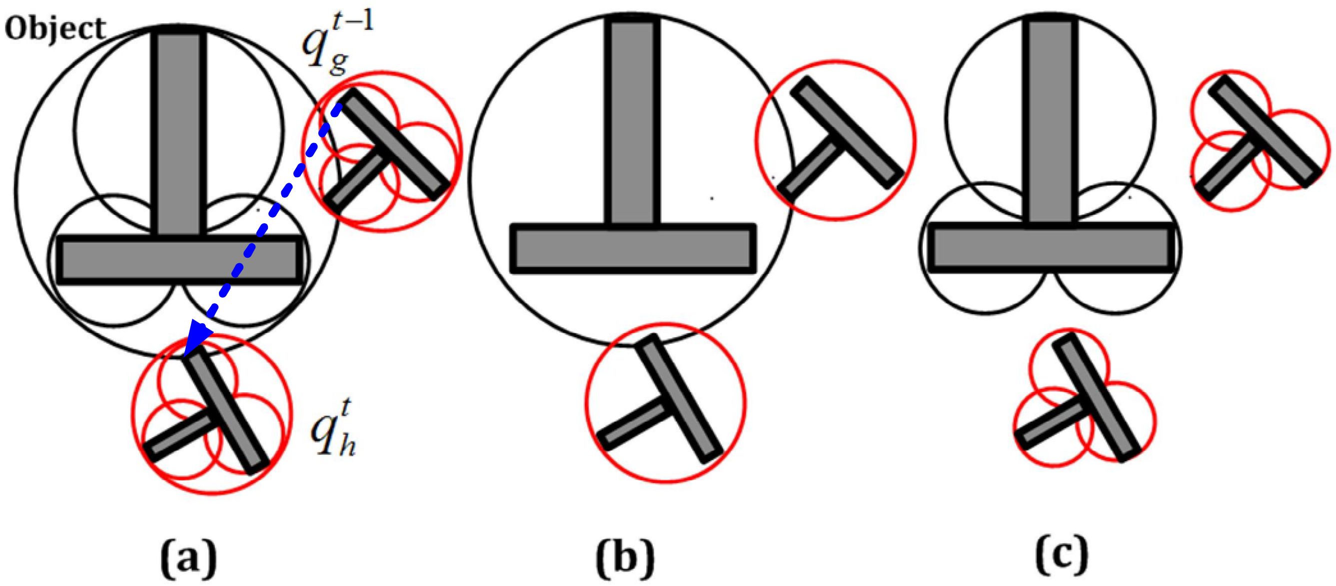
S-CCP method

- **Pros:**
  - Can simulate collisions between a pair of sphere-trees with detailed levels (e.g. level 5)
  - Can maintain 1kHz

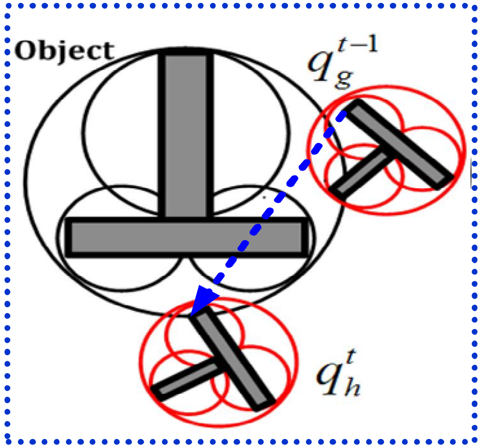
- **Cons:**
  - Cannot prevent tunneling effect, i.e. the tool will pop-through a thin object

SCCD

- Sphere-tree based continuous collision detection method for thin-objects

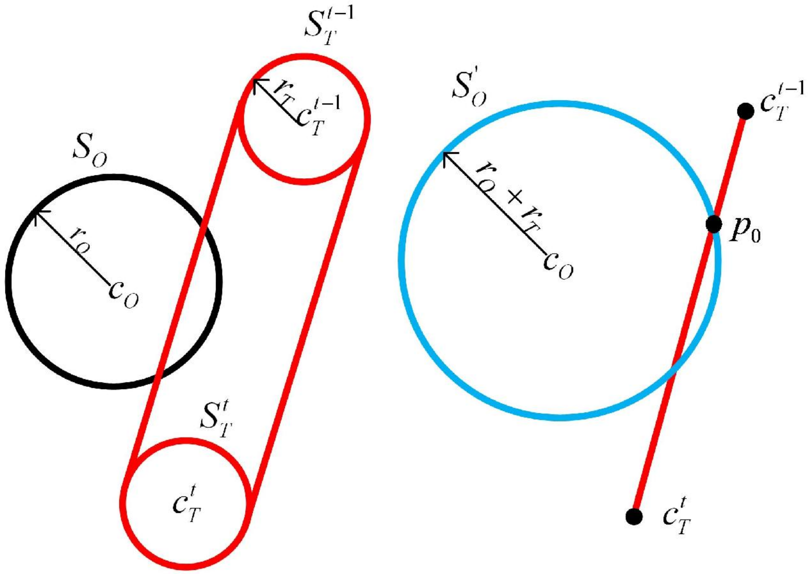


SCCD



- Compute the relative time when first contact occurs

$$t_{oc} = \frac{\overline{c_T^{t-1} p_0}}{\overline{c_T^{t-1} c_T^t}}$$



(a) (b)

LineSeg-sphere check

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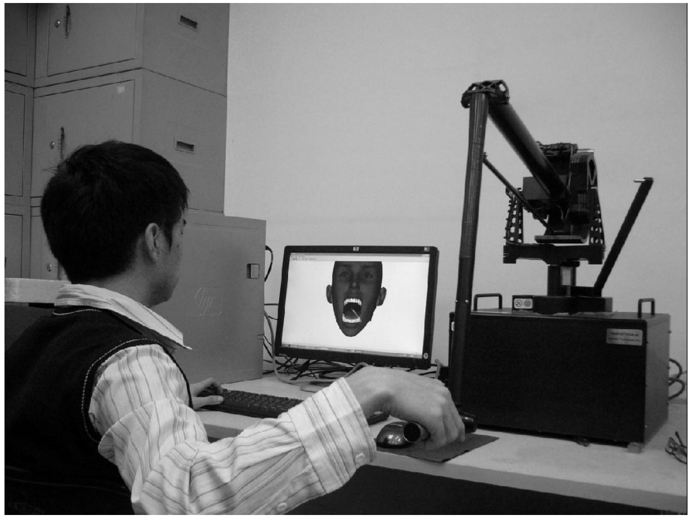
Experiments

- **Validation tasks:**
  - rigid-rigid multi-region contacts between two complex-shaped objects
  - rigid-deformable multi-region contacts between two complex-shaped objects
  - Manipulation against small-sized objects such as removing a small calculus using a dental scaler

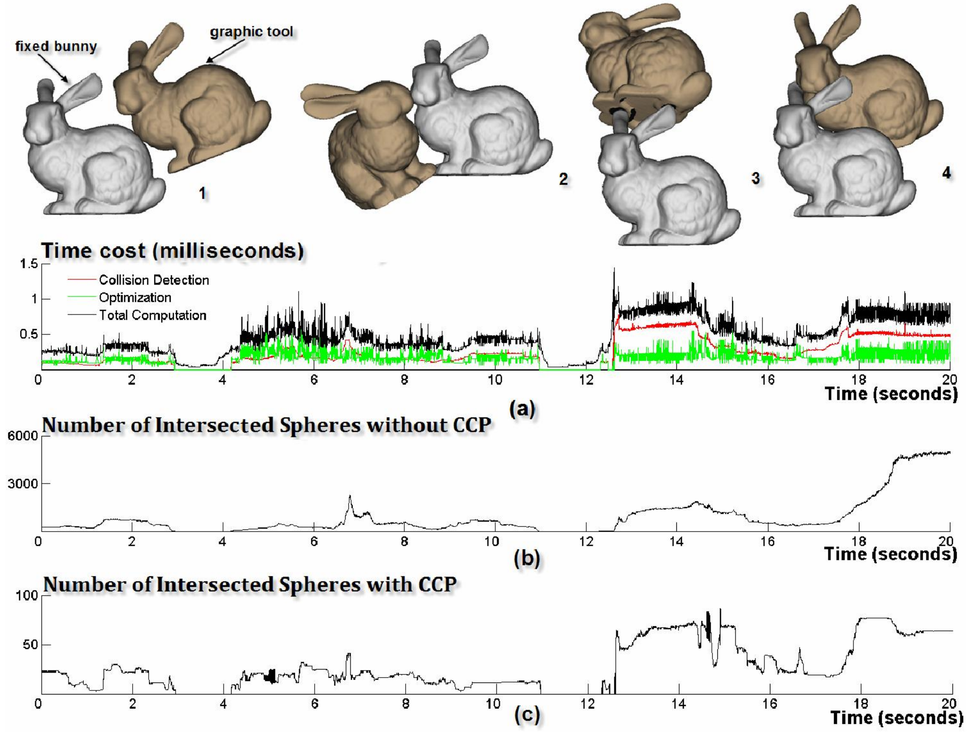


Rigid-rigid contacts

- Videos

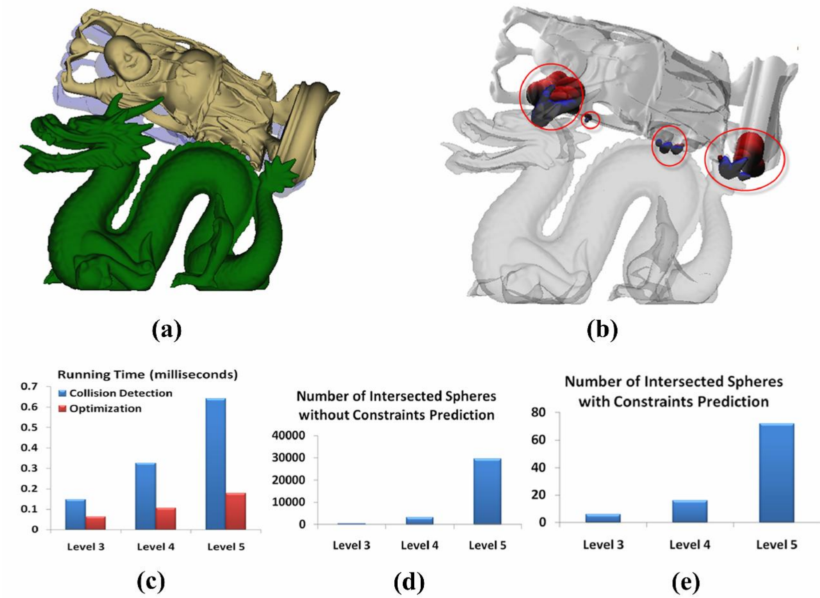
Rigid-rigid contacts

- Top: Four key states of the interaction (the white bunny is static)
- Plot (a): Time cost of the main algorithms in our approach
- Plot (b): The number of intersected spheres with conventional collision detection
- Plot (c): The number of intersected spheres with CCP method



Rigid-rigid contacts

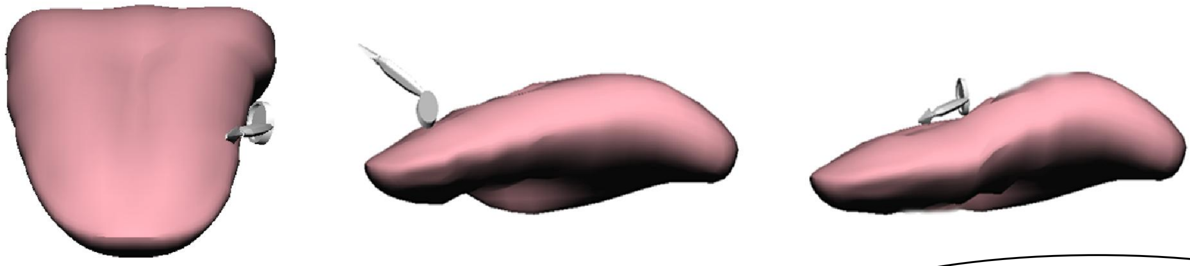
- Haptic simulation of multiregion contacts involving statues of a moving Buddha and a static dragon

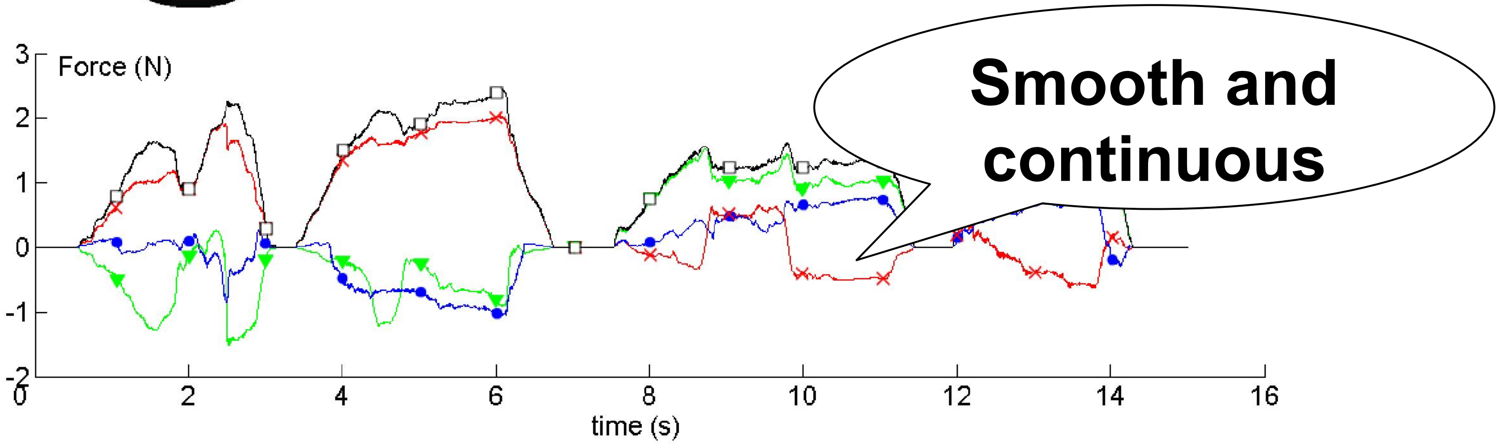


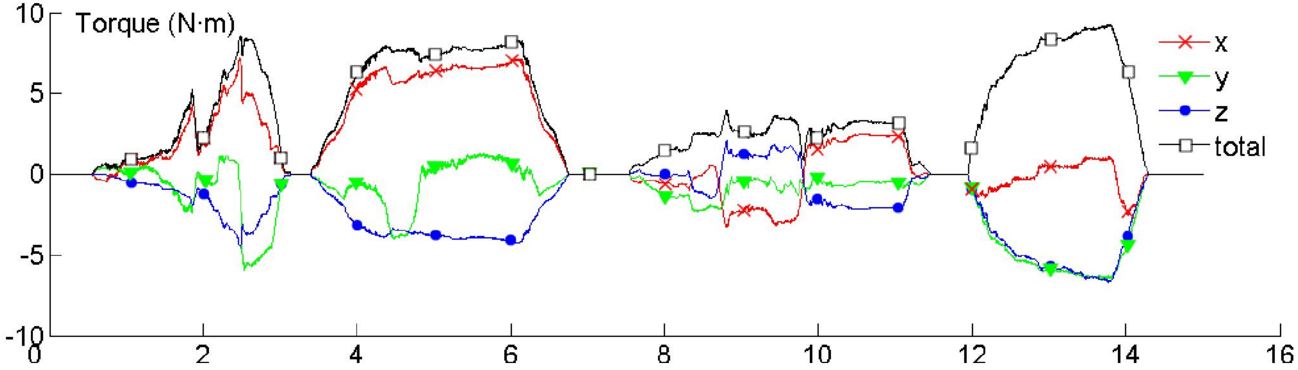
Experiments Video

- Video of deform simulation

Deformation of the tongue



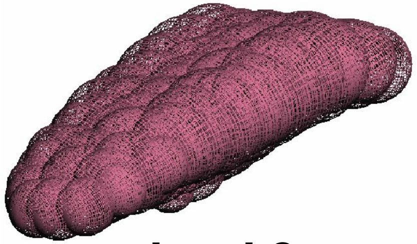


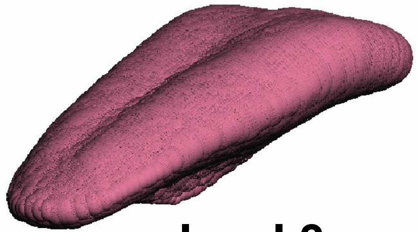


Computation efficiency

Two cases	Collision detection	Deformation	Optimization	Haptic loop
Case 1	0.13 ms	0.34ms	0.16ms	1587Hz
Case 2	0.20 ms	0.34ms	0.13ms	1492Hz

- **Note**
  - Case 1: collision detection and optimization (level 2), deform skeleton (level 2)
  - Case 2, collision detection and optimization (level 3), deform skeleton (level 2)


level 2


level 3

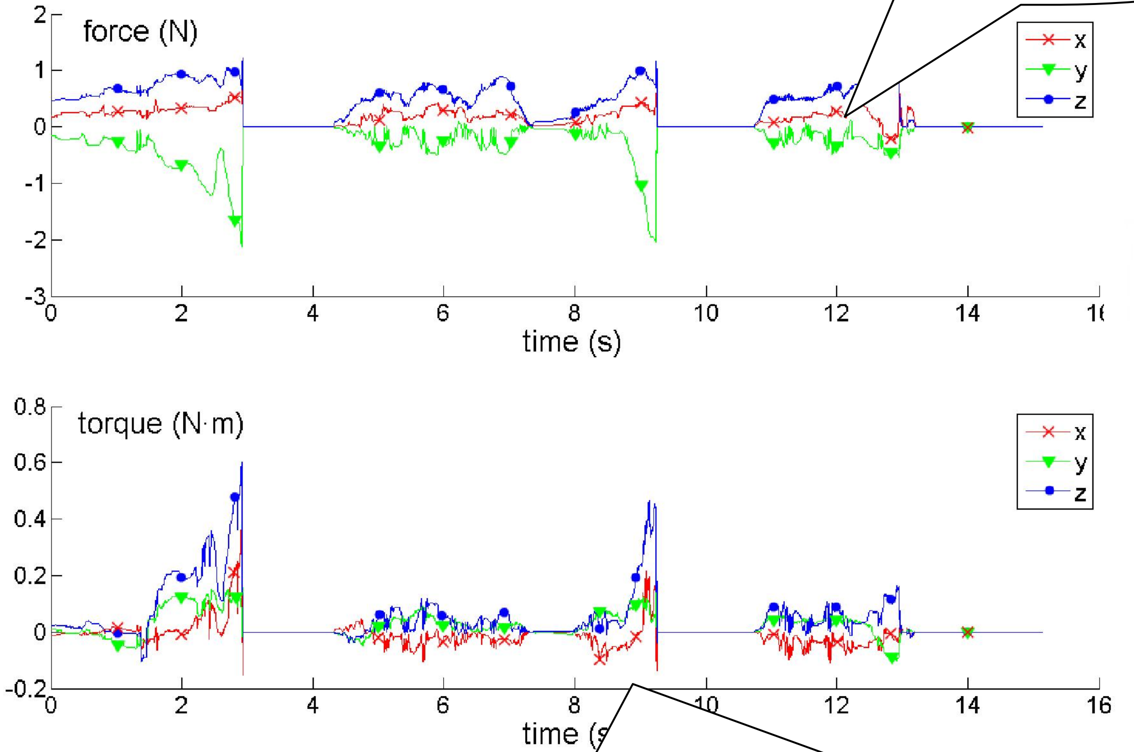
Experiments Video

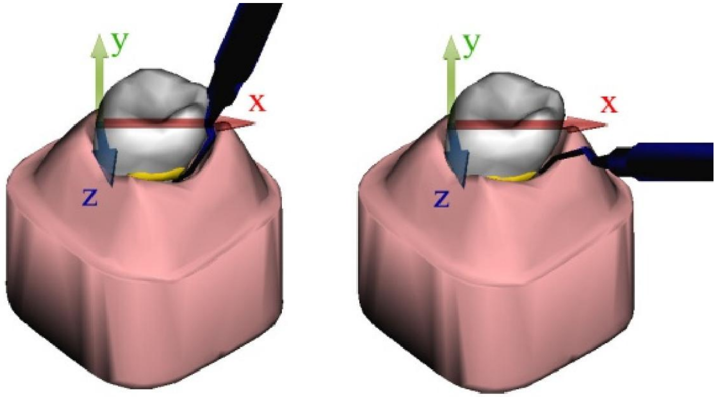
- Video of calculus removal

Removal of block-shaped

ca

Smooth and continuous





Sudden drops of feedback force at the 3rd, 9th, and 13th second, which means that the scaler was released by the calculus

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Conclusions

- A configuration-based optimization method for constraint-based haptic rendering
  - Visual artifacts are avoided
  - Virtual coupling is avoided without losing stability
- Sphere-tree based collision detection
  - A sphere tree to efficiently do collision detection
  - A *contact constraint-prediction* (CCP) method could reduce the number of constraints
  - *A sphere-tree based continuous collision detection* (SCCD) method to prevent pop-through problems for haptic interaction against thin objects

Future work

- Future work
  - Acceleration of sphere-tree based collision detection by GPU
  - Simulation of cutting, suturing etc.

References

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2. D. Wang, S. Liu, X. Zhang, Y. Zhang and J. Xiao, Six-degree-of-freedom Haptic Simulation of Organ Deformation in Dental Operations, ***IEEE International Conference on Robotics and Automation, ICRA 2012***, May 14-18, 2012, St. Paul, Minnesota, USA, pp. 1050-1056.
3. D. Wang, S. Liu, J. Xiao, J. Hou, Y. Zhang. Six Degree-of-Freedom Haptic Simulation of Pathological Changes in Periodontal Operations. ***2012 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS2012).*** Vilamoura, Algarve, Portugal October 7-12, 2012. pp. 39-45
4. D. Wang, X. Zhang, Y. Zhang and J. Xiao, Configuration-based Optimization for Six Degree-of-Freedom Haptic Rendering for Fine Manipulation, ***IEEE International Conference on Robotics and Automation, ICRA 2011***, May 9-13, Shanghai, China, pp. 906-912.
5. Xin Zhang, Dangxiao Wang, Yuru Zhang and Jing Xiao, Configuration-based Optimization for Six Degree-of-Freedom Haptic Rendering Using Sphere-trees, ***Proc. of the IEEE International conference on Intelligent robot and systems, IROS 2011***, September 25-30, 2011, San Francisco, California, U.S. , pp. 2602-2607.

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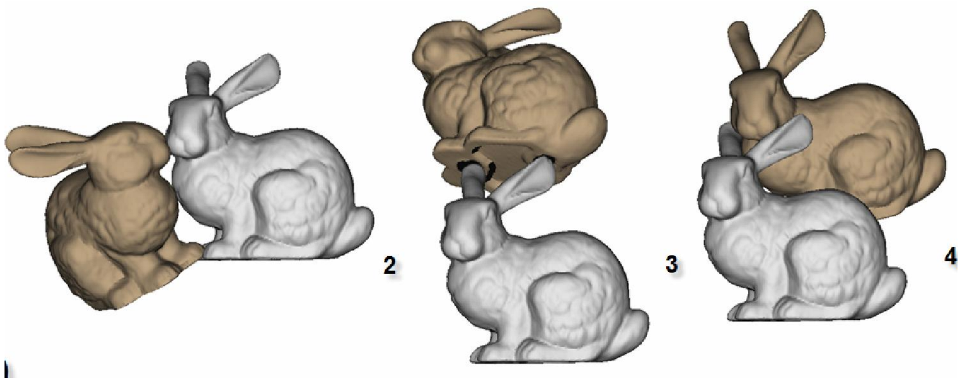
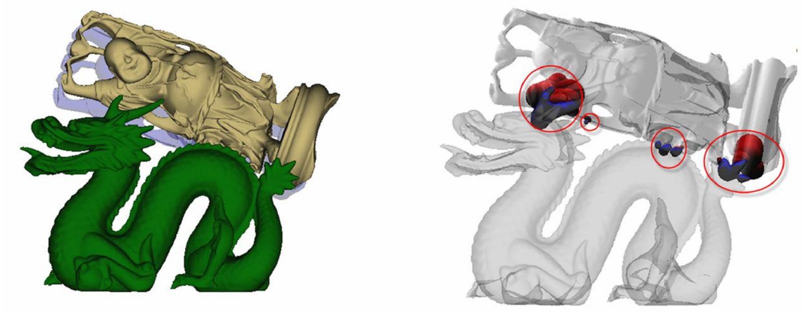
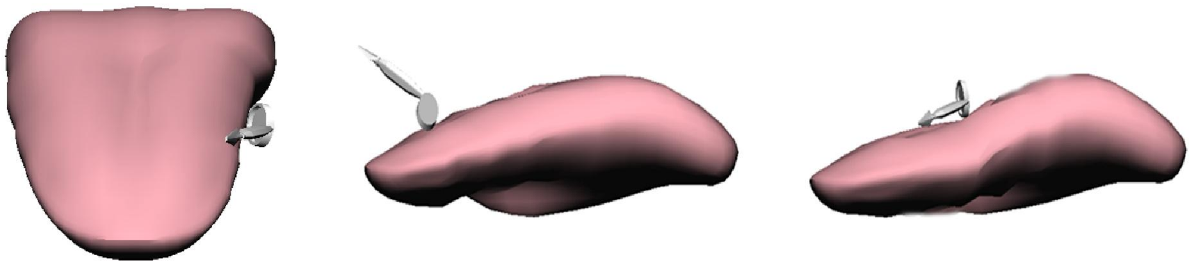
UNC CHARLOTTE

Thank you
Welcome to try our demos



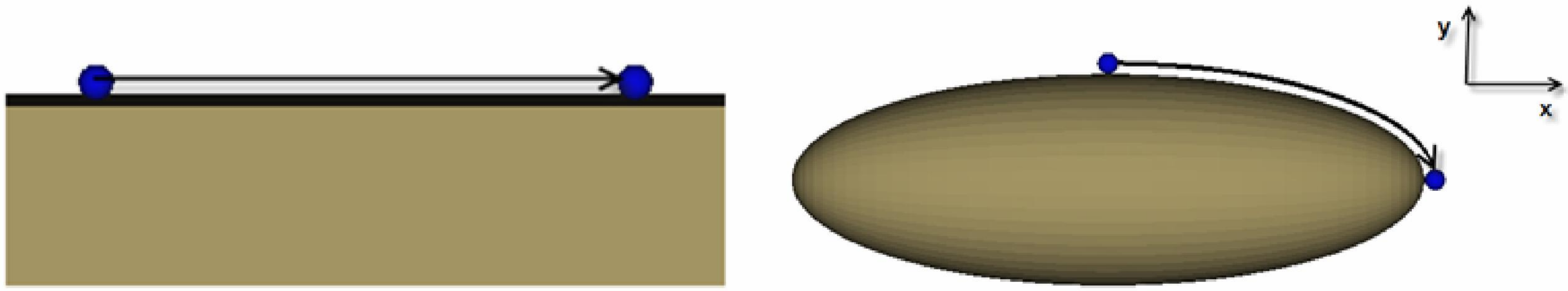




Sphere-tree based collision detection for constraint-based 6-DOF haptic rendering *WHC2013* **Email: hapticwang@buaa.edu.cn**

Accuracy

- Comparing force/torque signals from a ground-truth model and a target model



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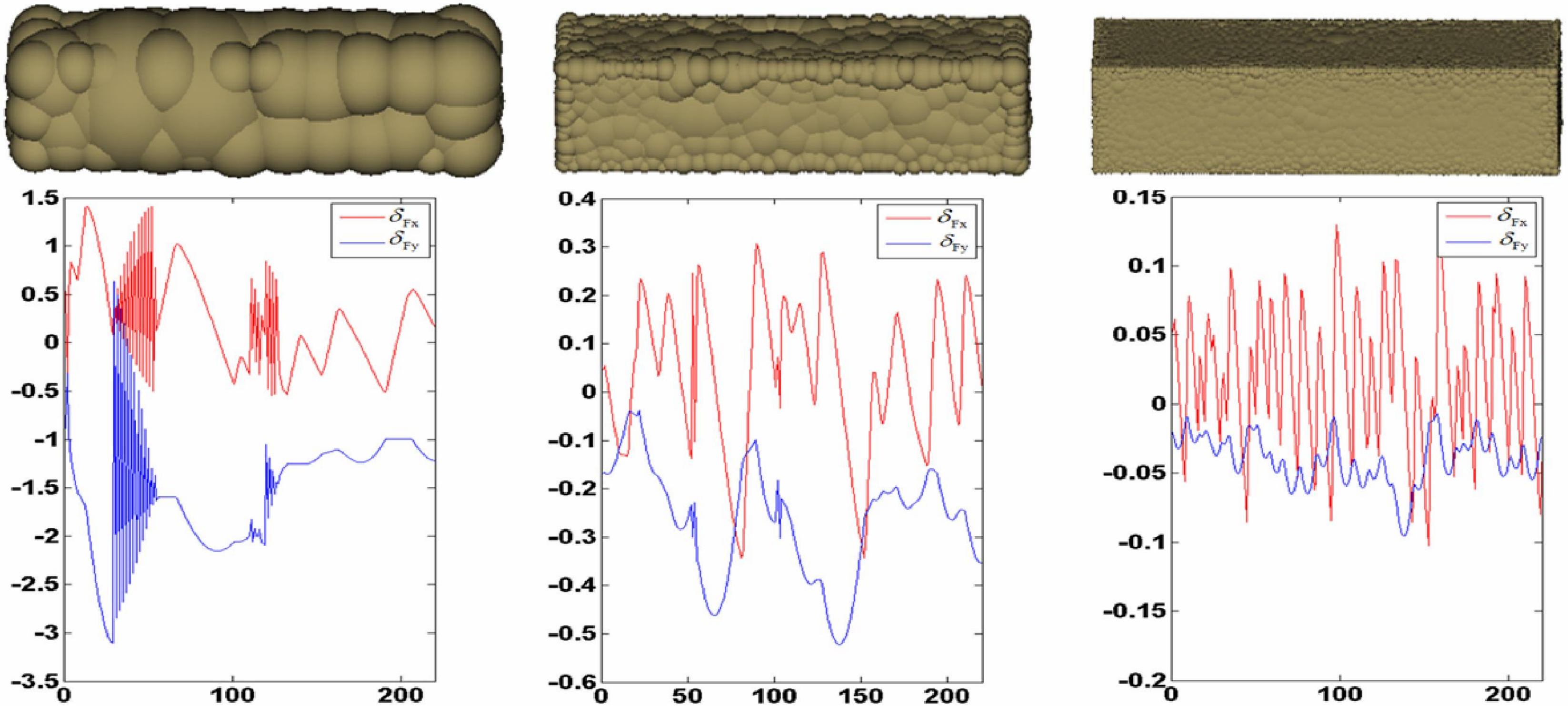
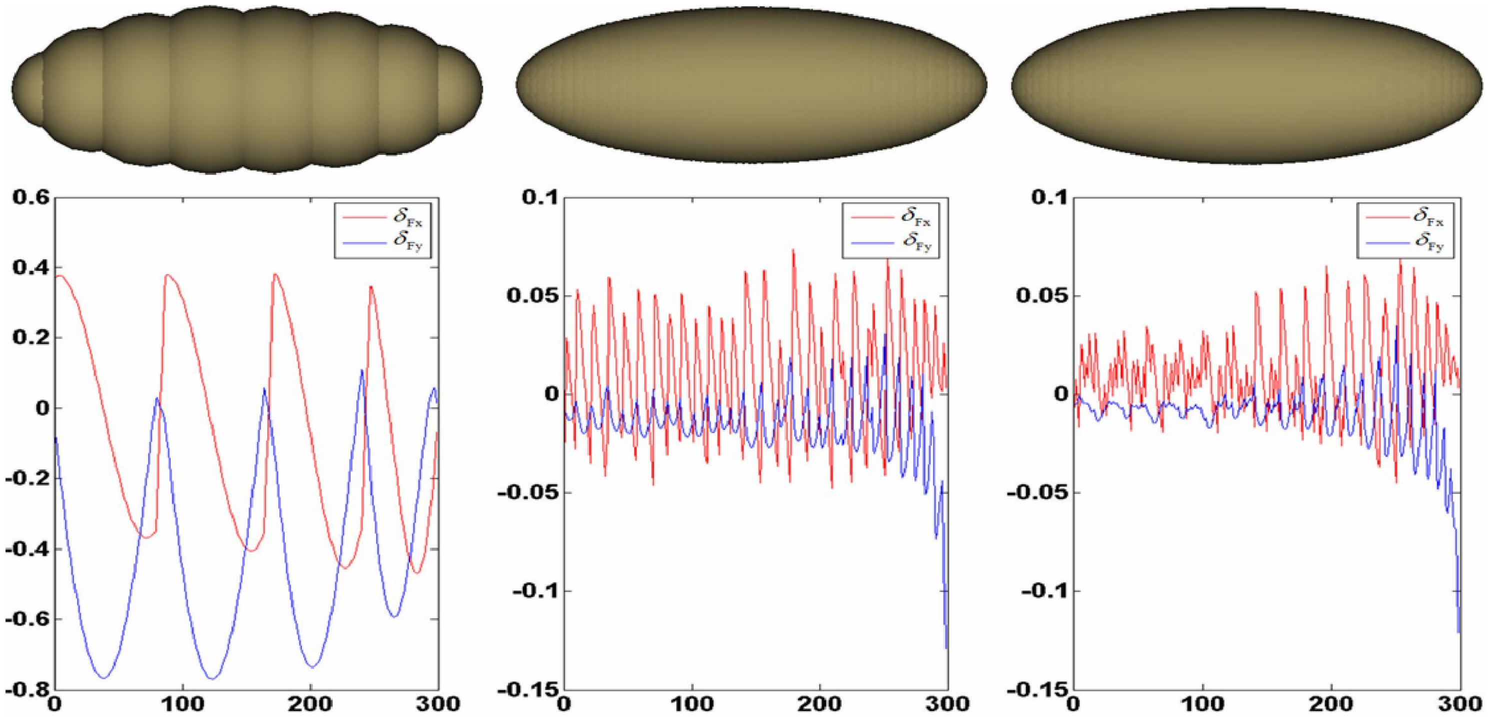


Accuracy

➢ **Comparing force/torque signals from a ground-truth model and a target model**

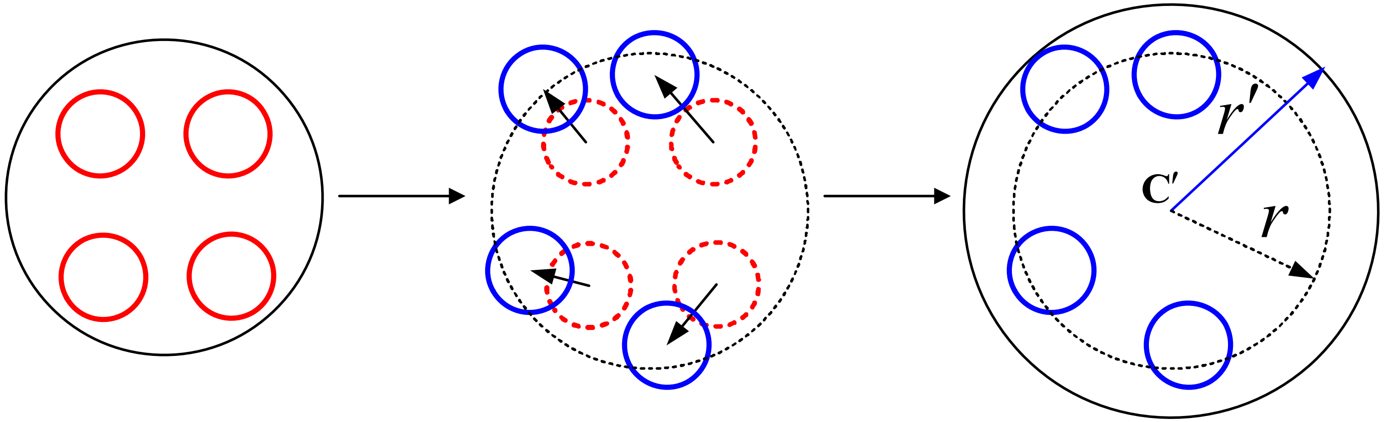


Accuracy

- For the cube model
  - the average force error under level 4 sphere-tree model is at about 0.05.
- For the ellipsoid model
  - the maximum force error under level 3 sphere-tree model is at about 0.05.
- Human's JND (just noticeable difference) for force magnitude is about 6-8 percent

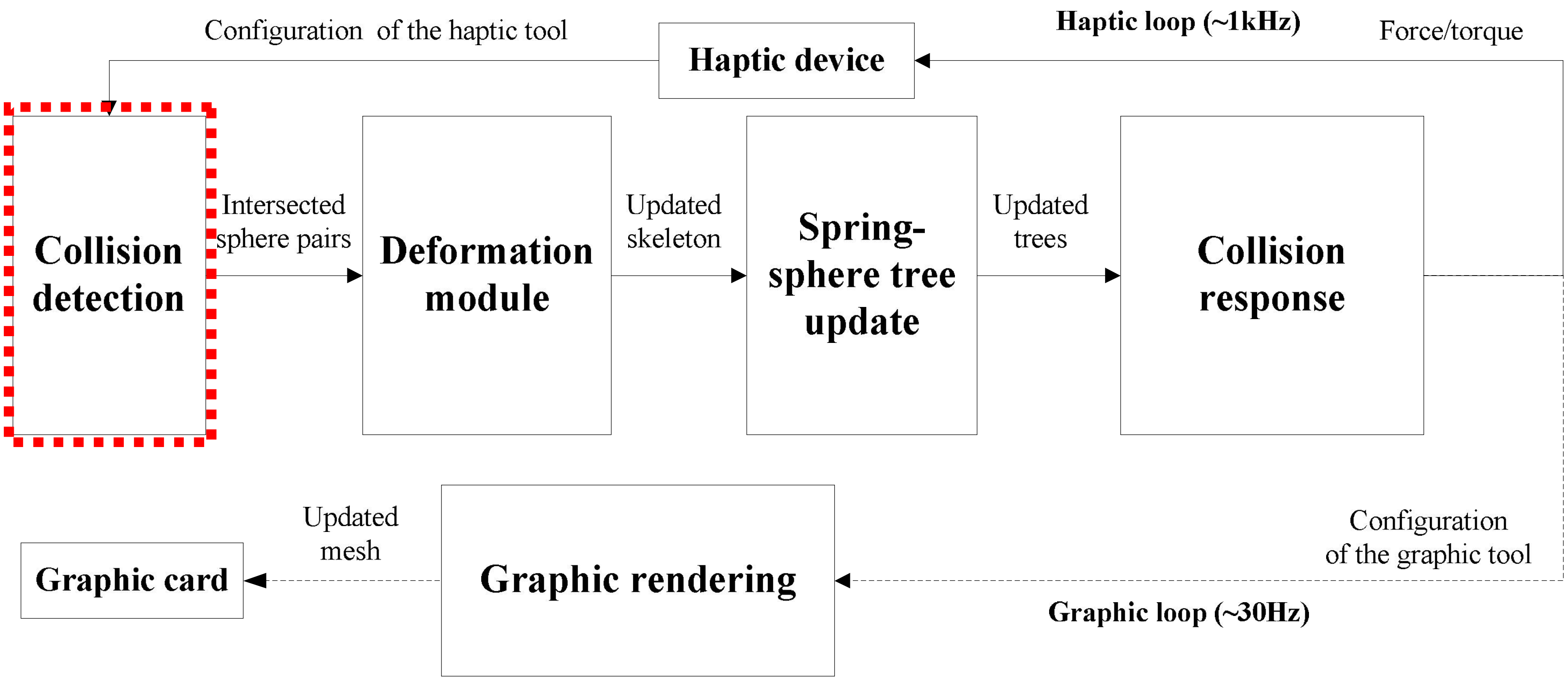
Update of Spheres

- Two kinds of update:
  - from children nodes to parents' nodes
  - from parents' nodes to children nodes



$$\begin{cases} \mathbf{C}' = \mathbf{C} \\ r' = \max\left(\left|\mathbf{CC}_i\right| + r_i\right)_{i=1,\cdots,8} \end{cases}$$

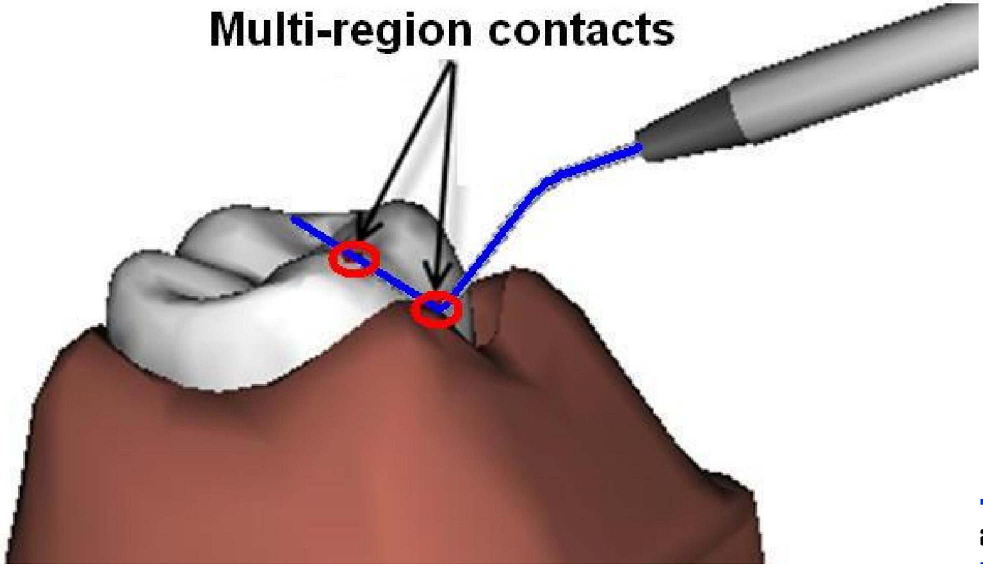
Flowchart of rendering

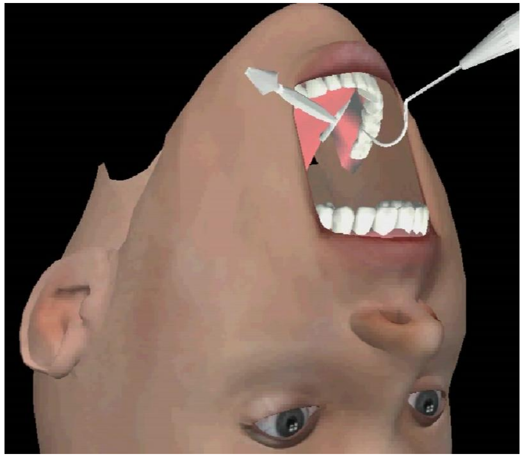


Haptic Simulation of Deformation

- **Deformation in surgical operations**
  - Using a mirror to deform a tongue
  - Using a probe to remove calculus

- **Challenges for haptic simulation**
  - Multiple-region contacts
  - Six dimensional force and torque
  - Realistic, stable, and haptic rates





Spring-sphere tree model

- Hierarchical sphere tree
  - – Low Level (finer model): collision detection and optimization
  - – High level (coarser model): deformation
- Skeleton at a
  - – added spring