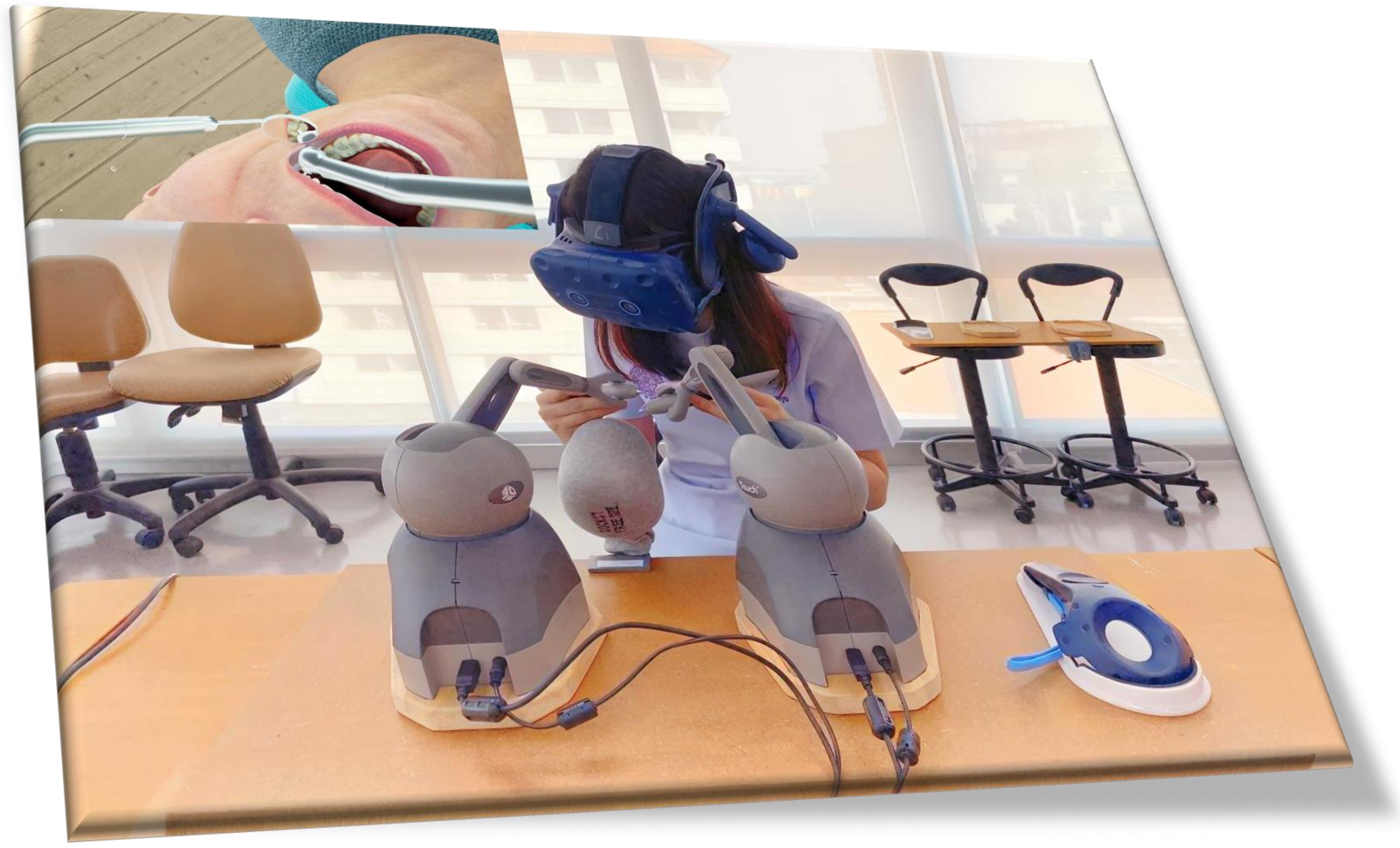
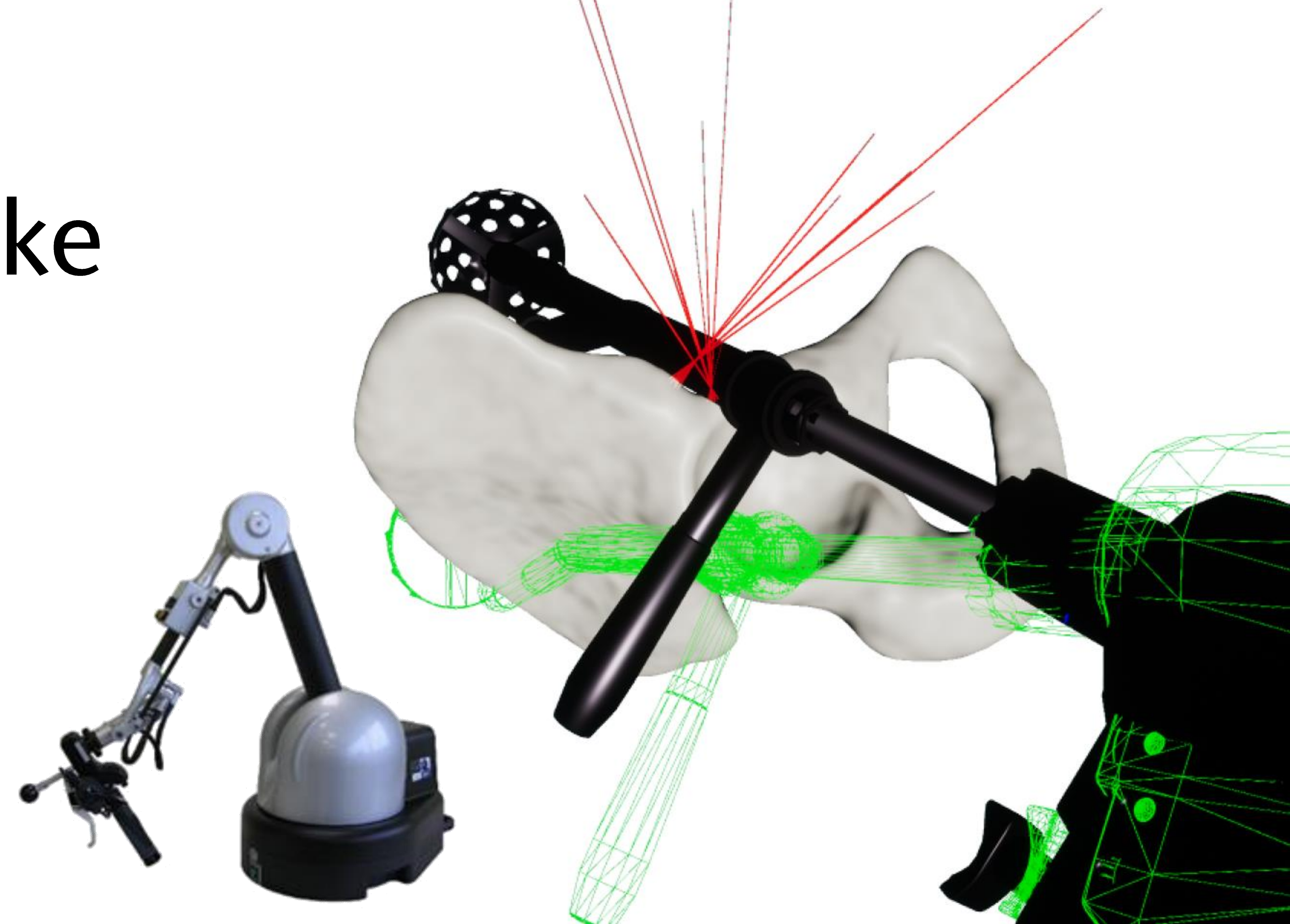
Immersive Medical VR Training Simulators with Haptic Feedback

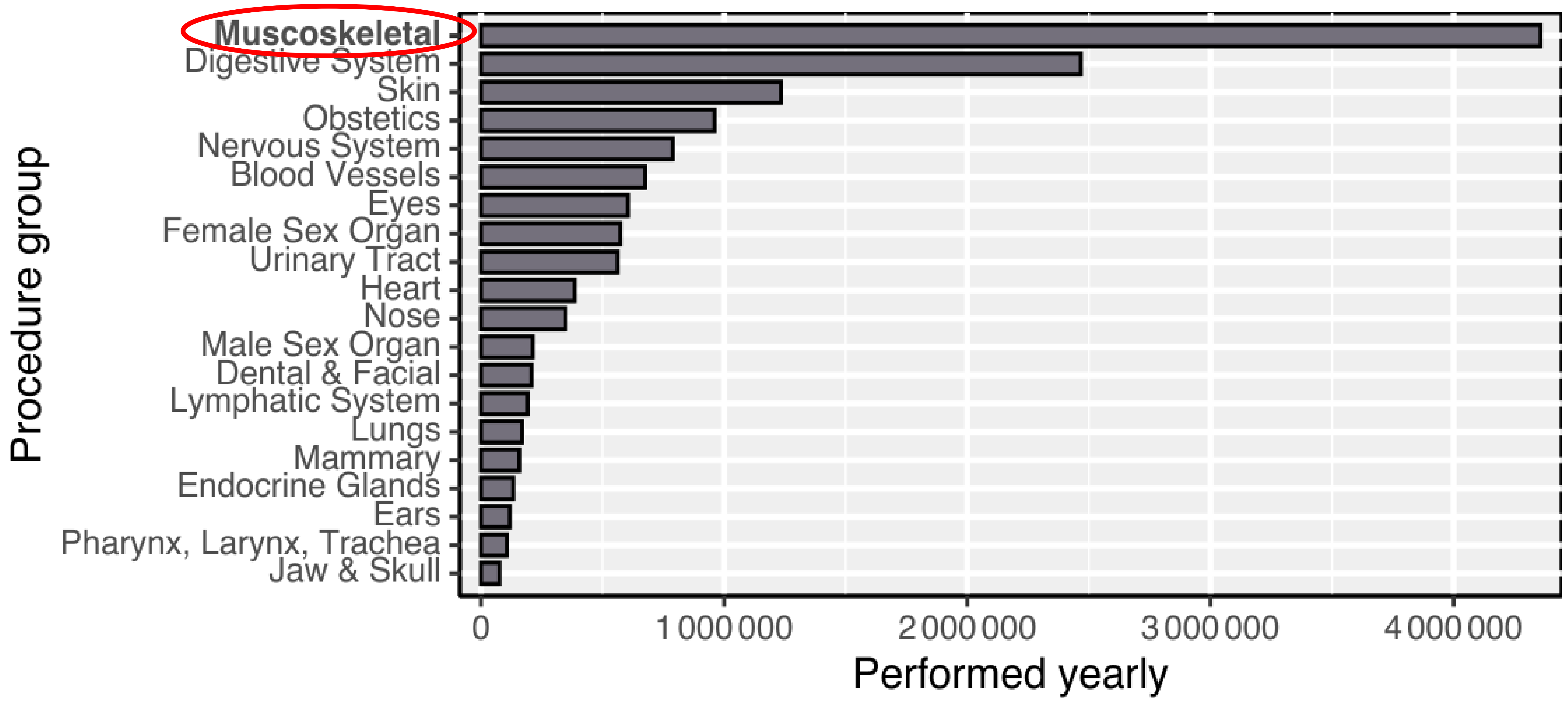
Maximilian Kaluschke

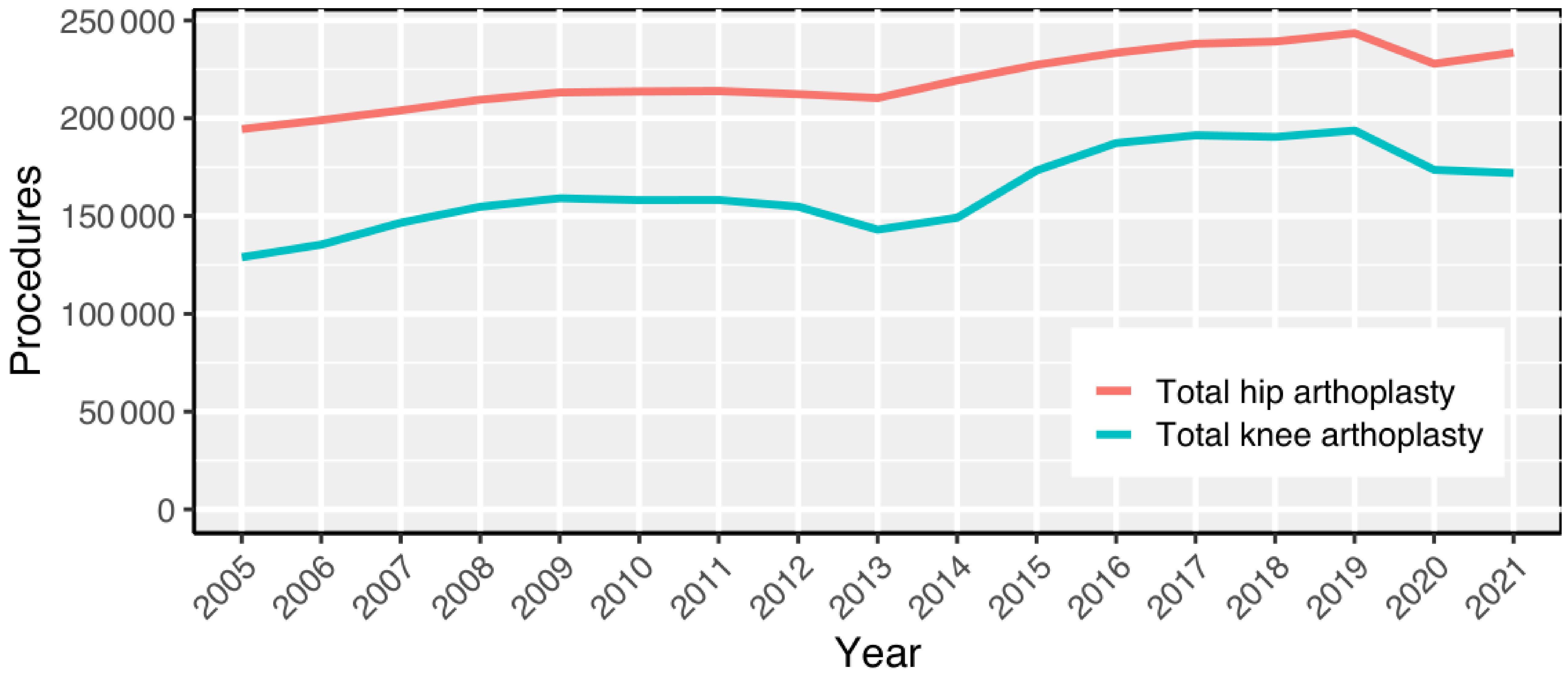




Challenges in Medicine

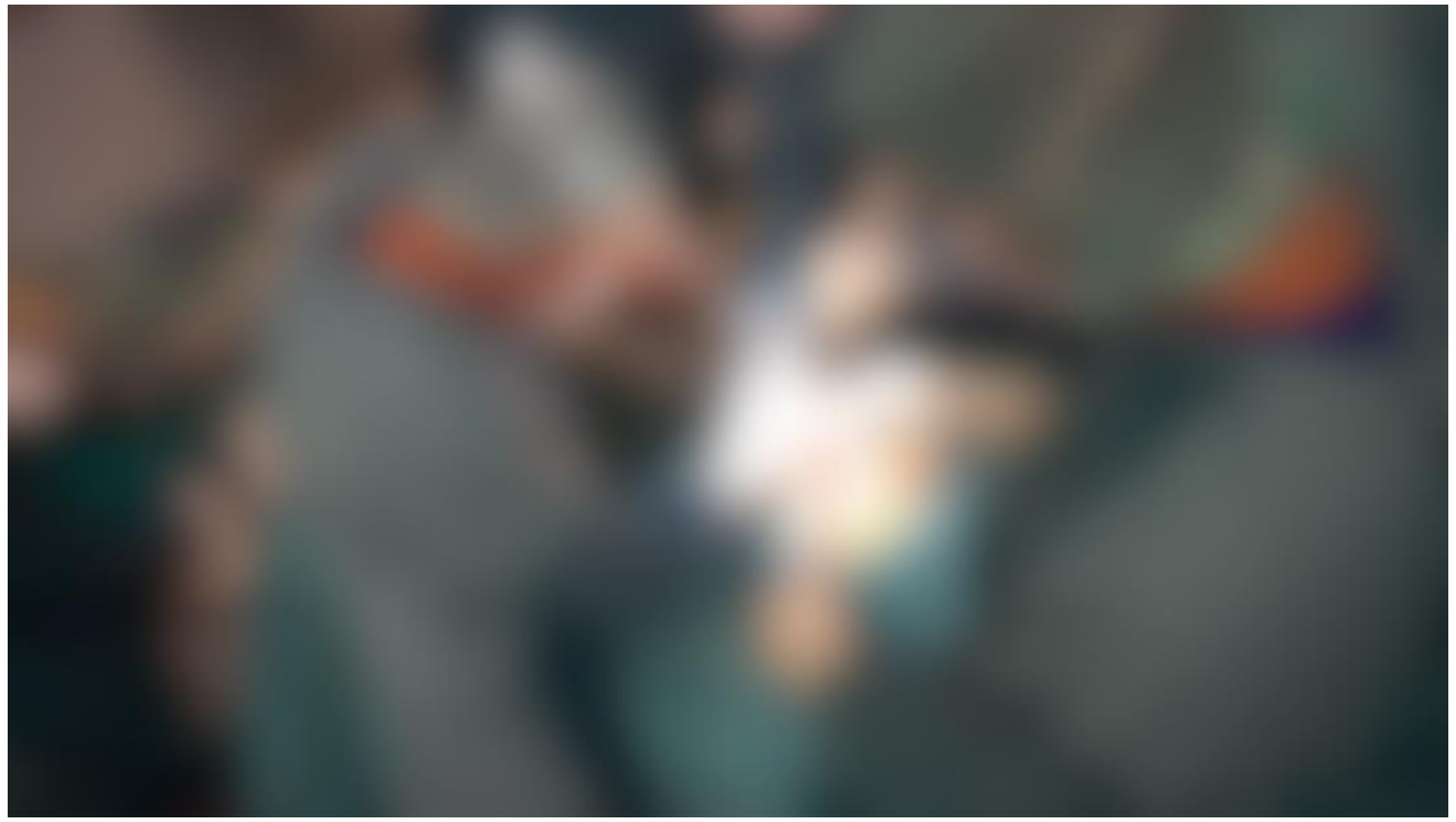
- Increased life expectancy
- Demographic shift
- Increased prevalence of mobility-related diseases
- Surgeon's experience critical
  - Early, frequent practice
- Teaching difficulties





Challenges in Medical Training

- Orthopedic surgeries
  - Navigation by feeling, limited sight
  - Large forces



- Dental surgeries
  - Psycho-motor challenges
  - Precise bi-manual manipulation
  - Mirrored navigation

Traditional Medical Training

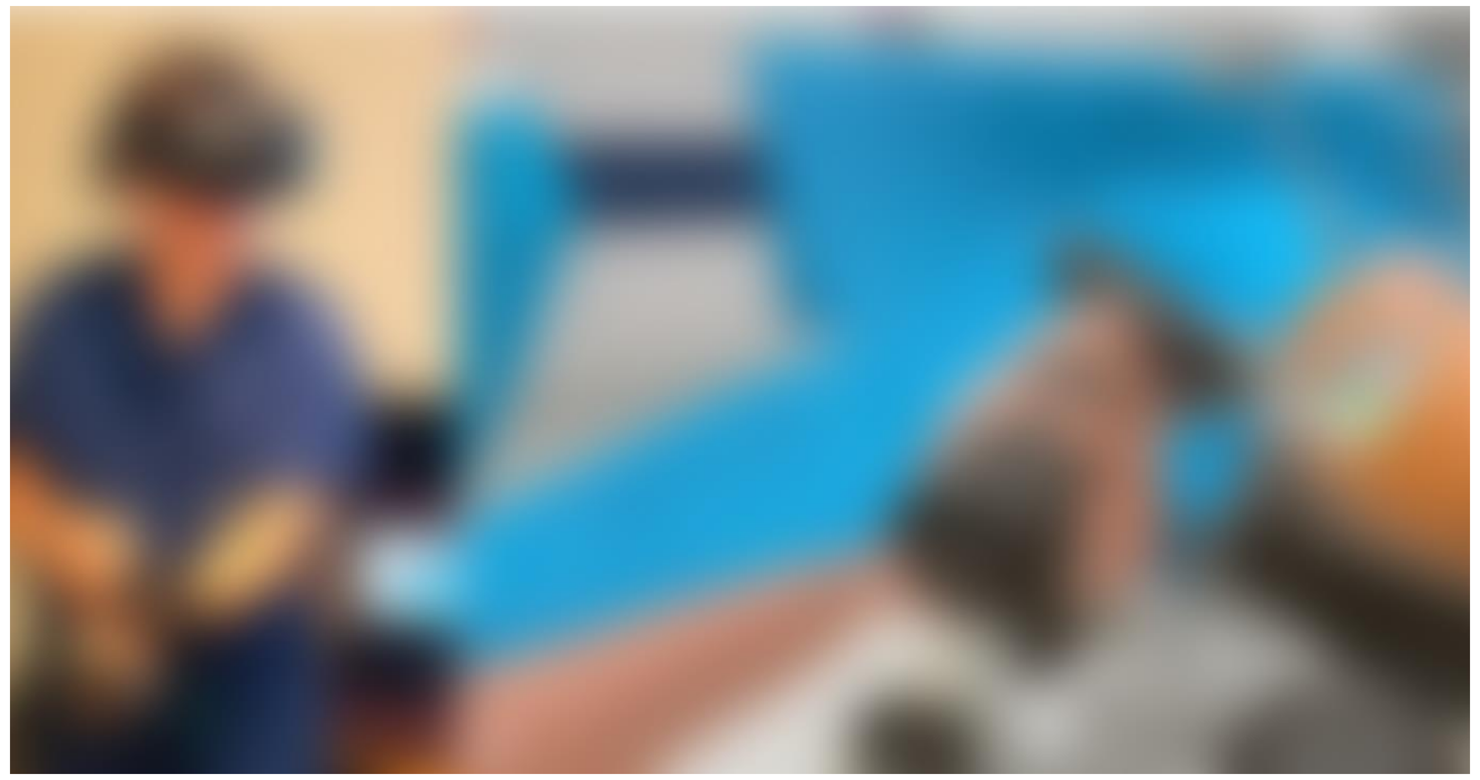
- Practice after students learn steps of procedures
- Practical training starts on physical dummies
  - Limited realism & high cost
- Donor organs when possible; realistic and safe
  - Low availability / high cost, no repeatability
- In practice, students assist during live procedures early
- VR simulators as complementary training

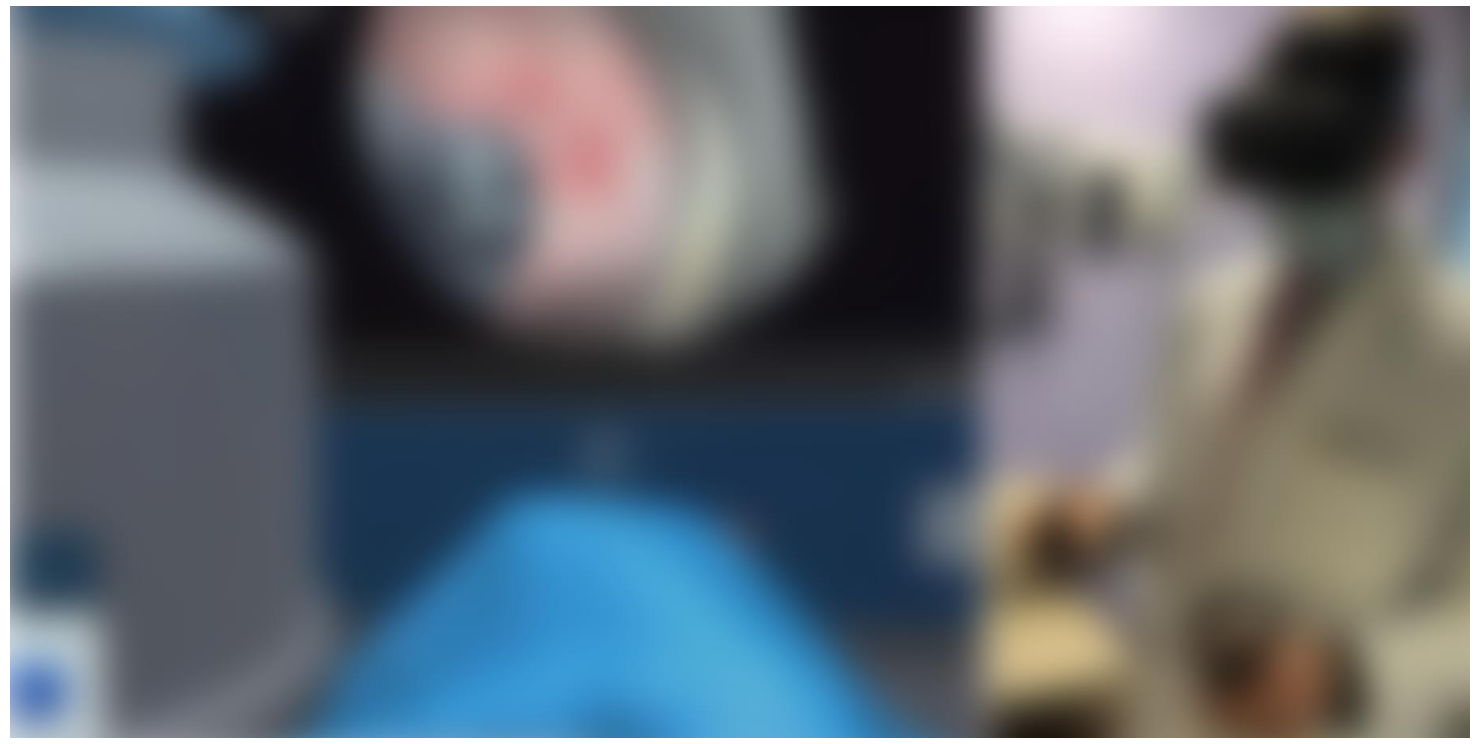
Potential of VR Simulators

- Repeatable, safe lessons
  - Low operational cost
  - Improve training quality
- Automated feedback
  - Reduce work for instructors
  - Objective feedback

VR Simulators State of the Art

- VR-only simulators
  - Logishetty et al. 2020
  - Rahman et al. 2024
- Haptic VR simulators
  - Bartlett et al. 2020
- Commercial hip surgery simulators
  - Fundamental Surgery, 2019



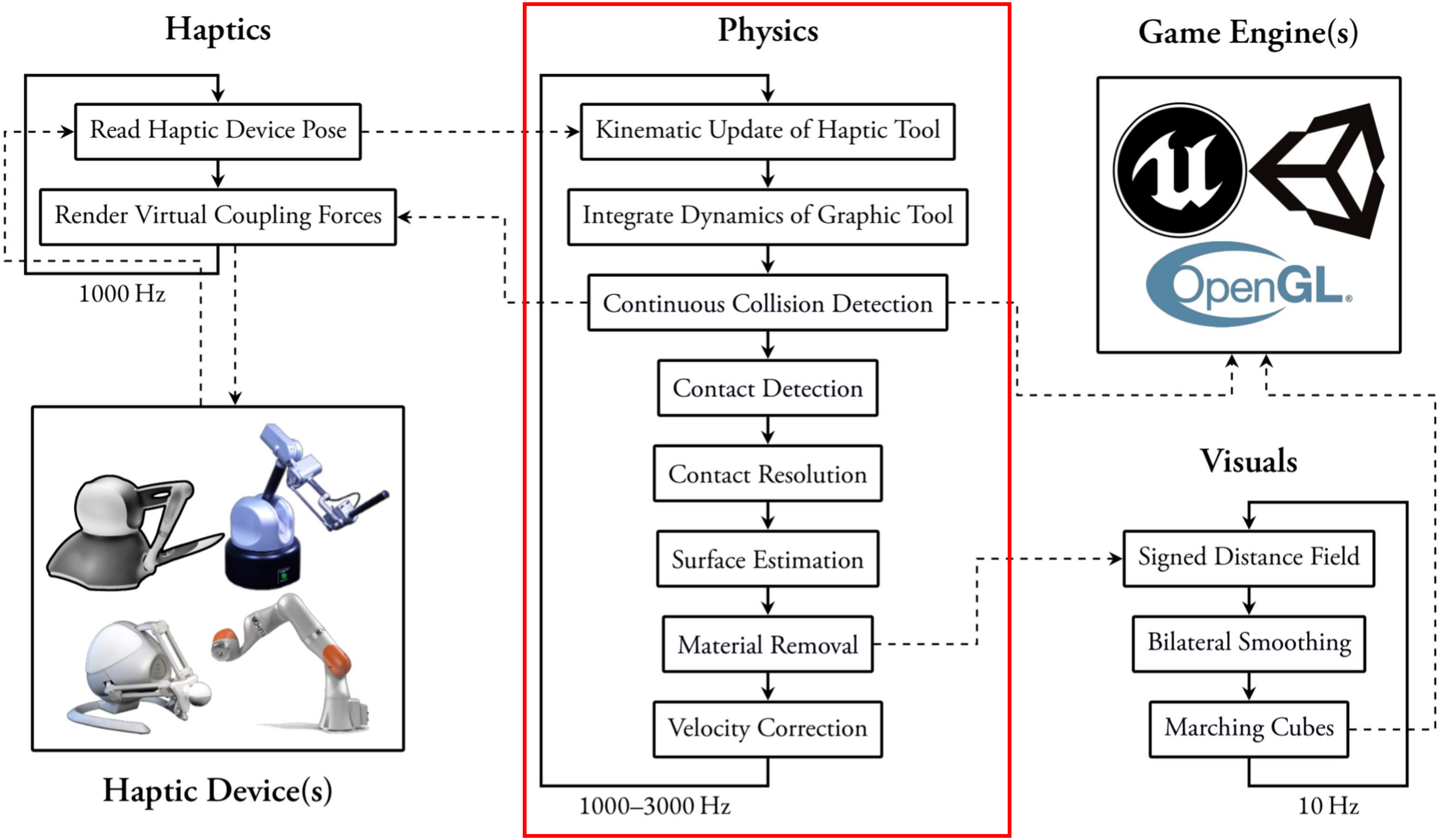


VR Simulators State of the Art

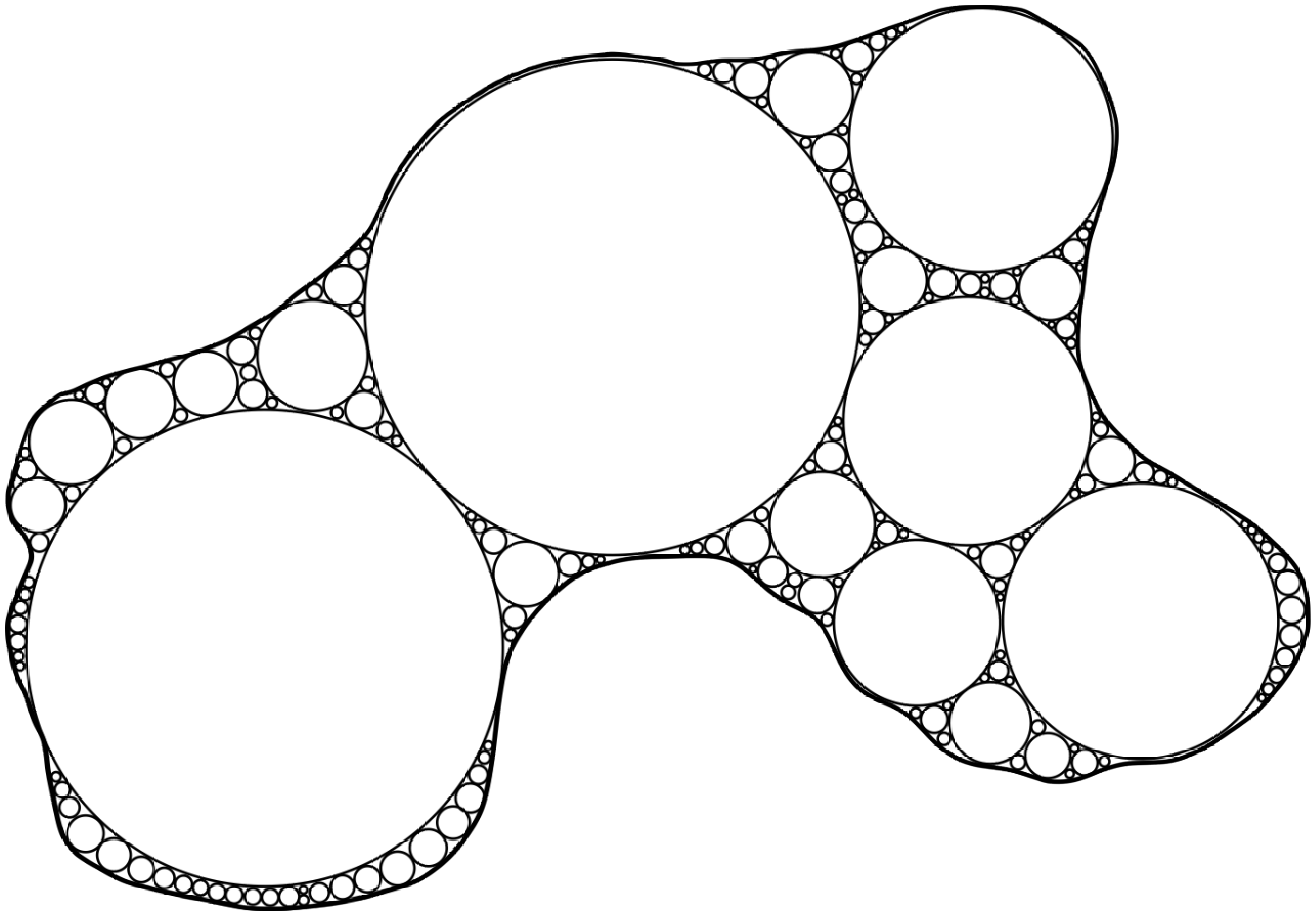
- Research gaps

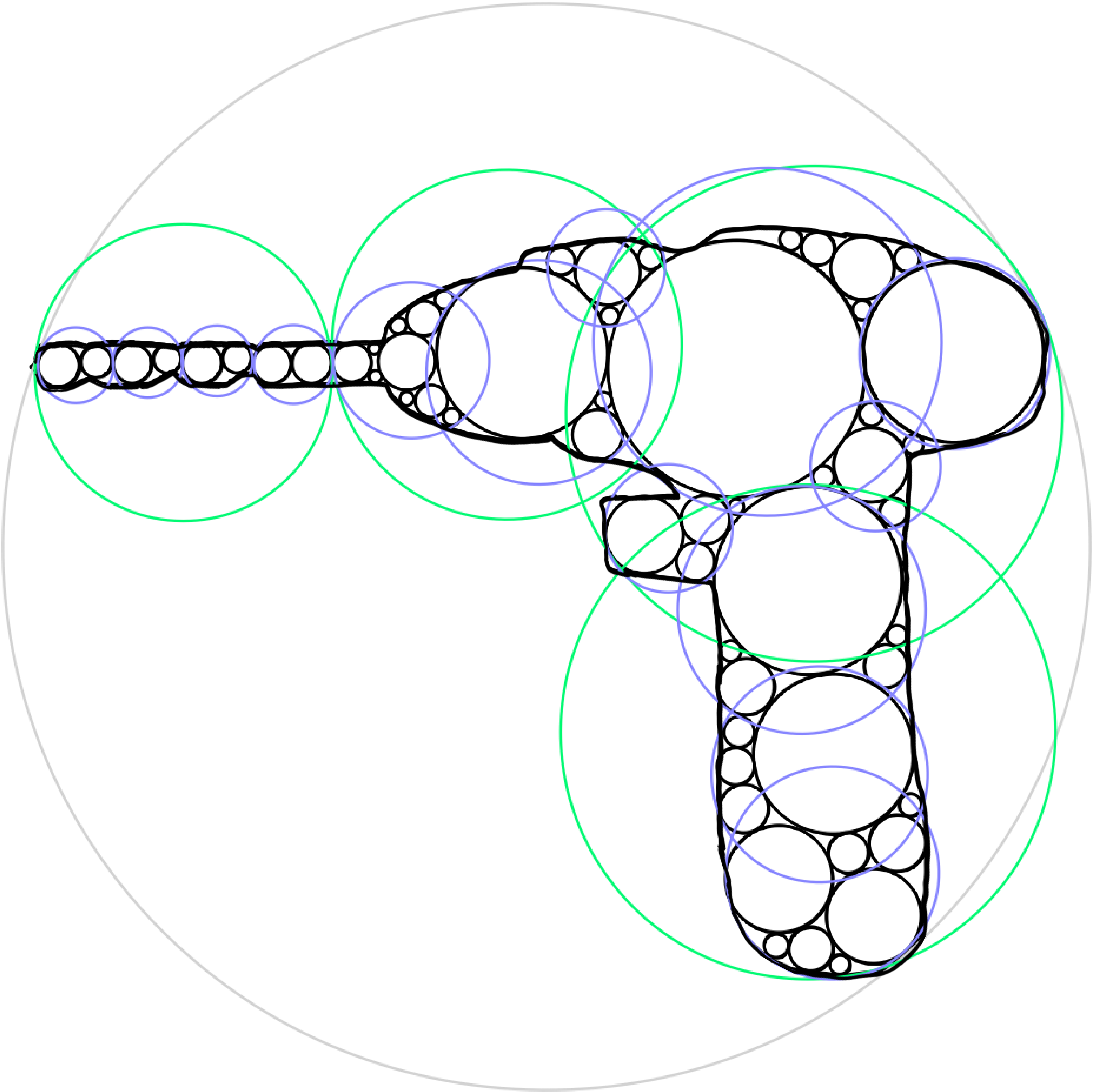
1. High-force haptic feedback
2. Stepless haptic material removal
3. Efficacy of HMD-based VR haptic simulators

Simulator as a System



Sphere Packing Volumetric Model





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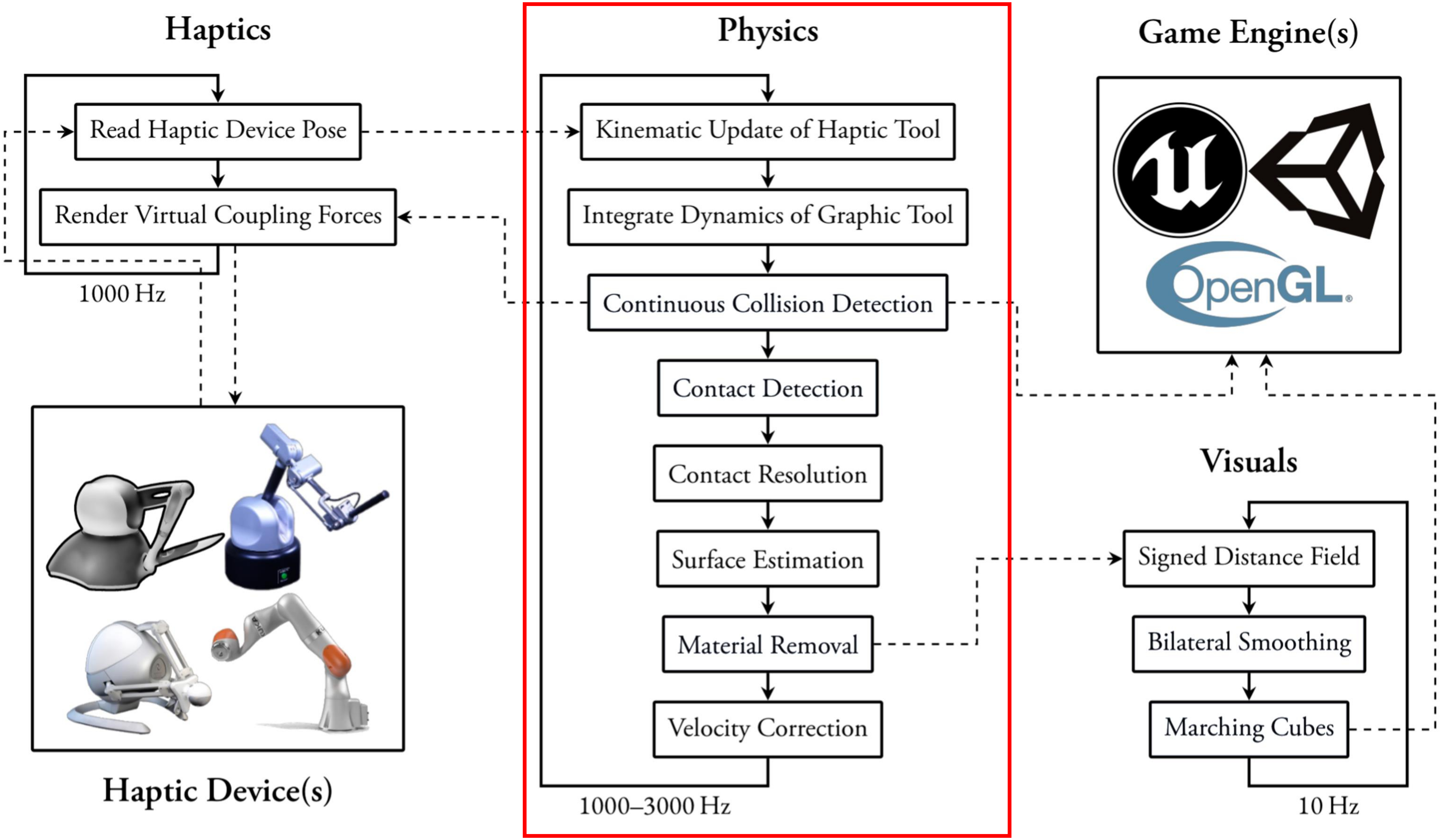
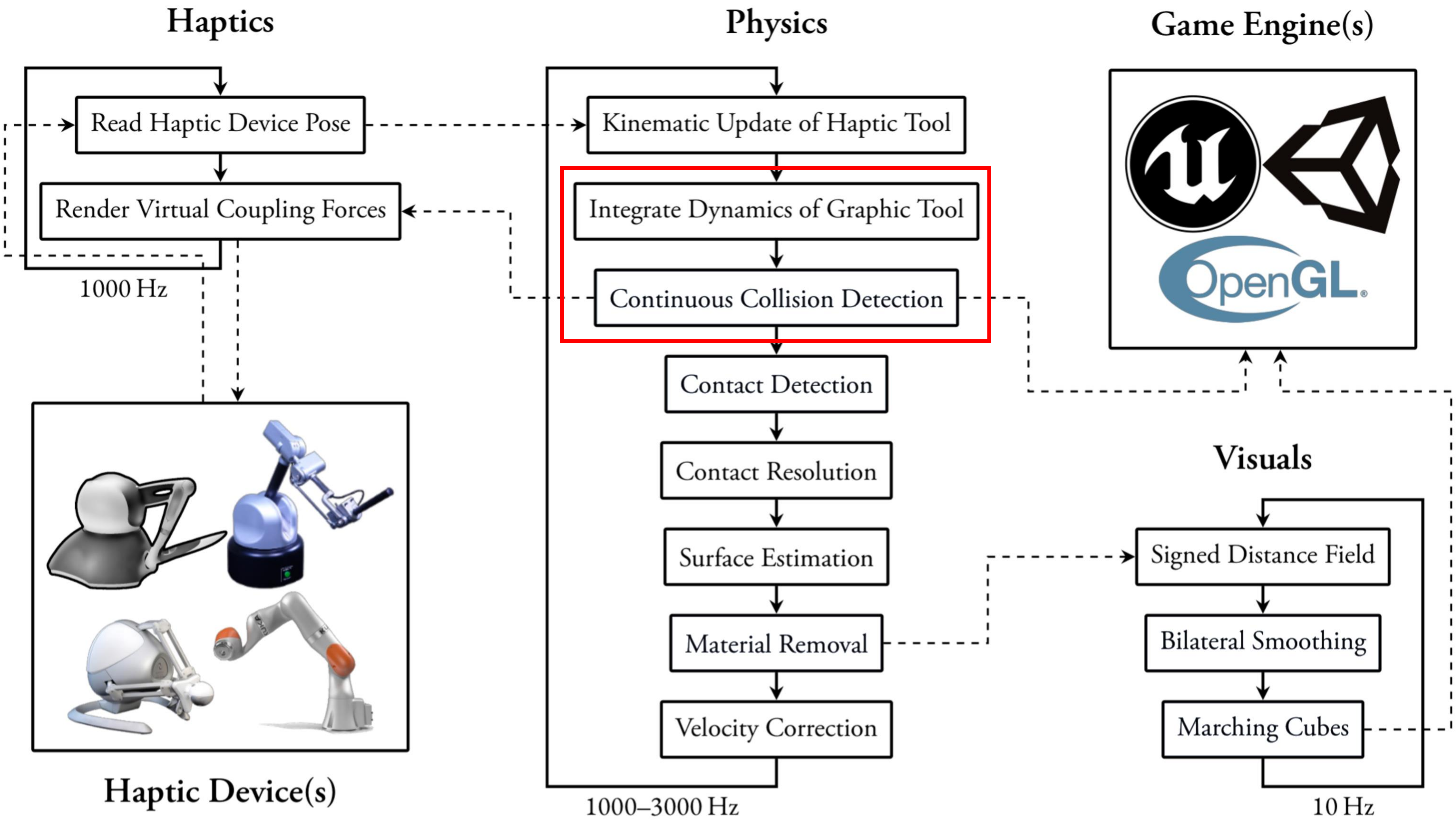
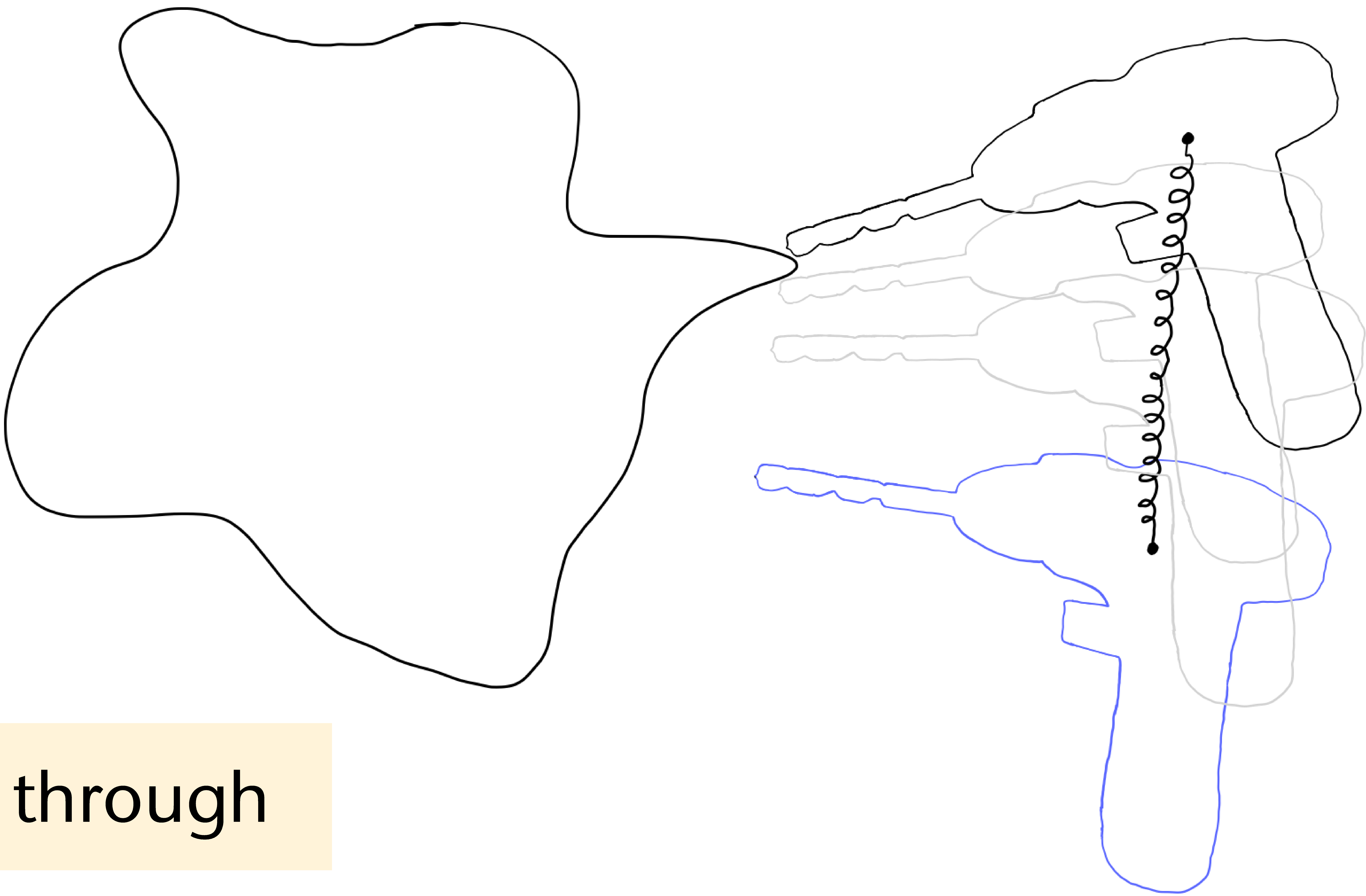


Simulator as a System

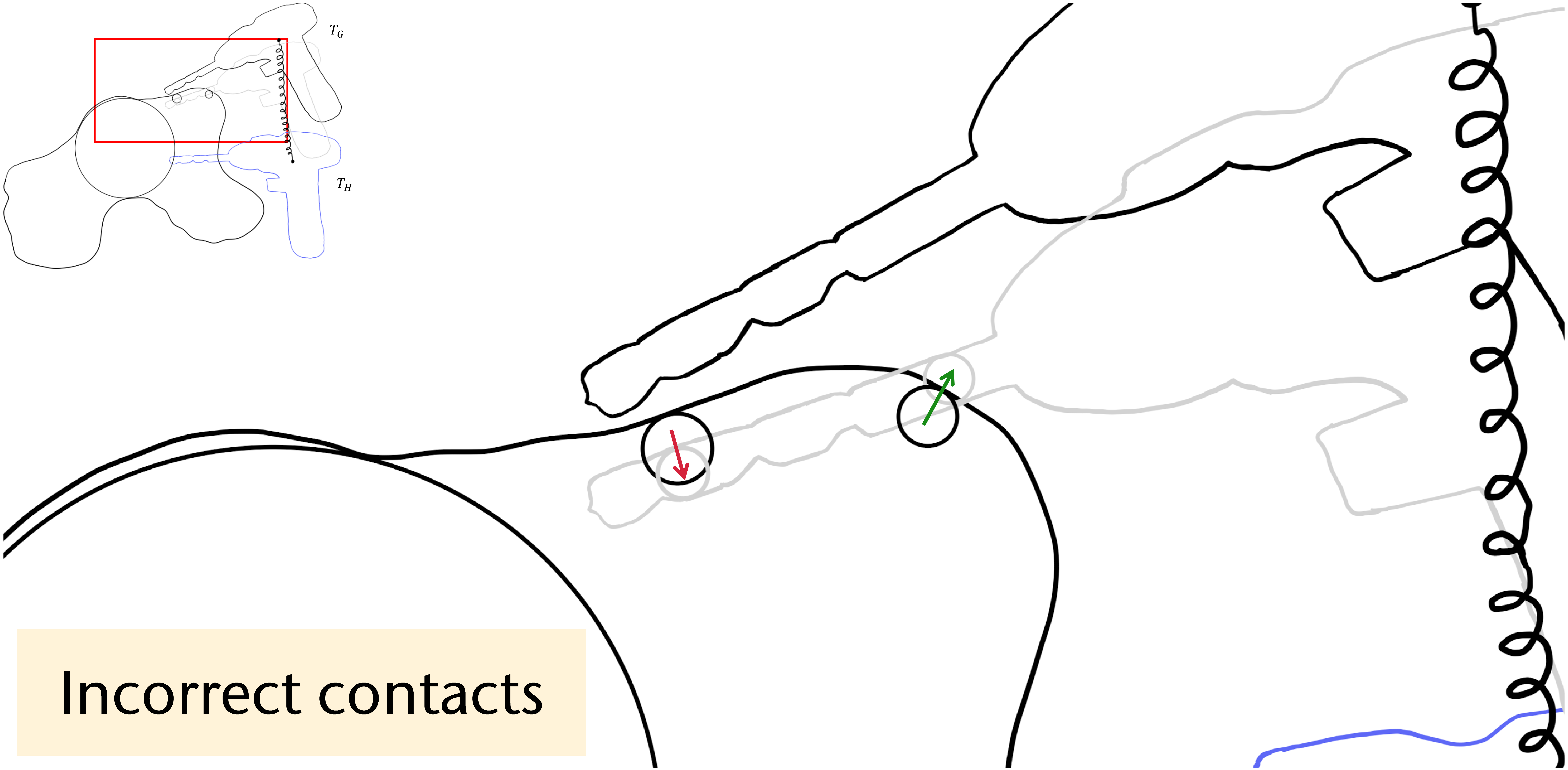


Simulation: Physics



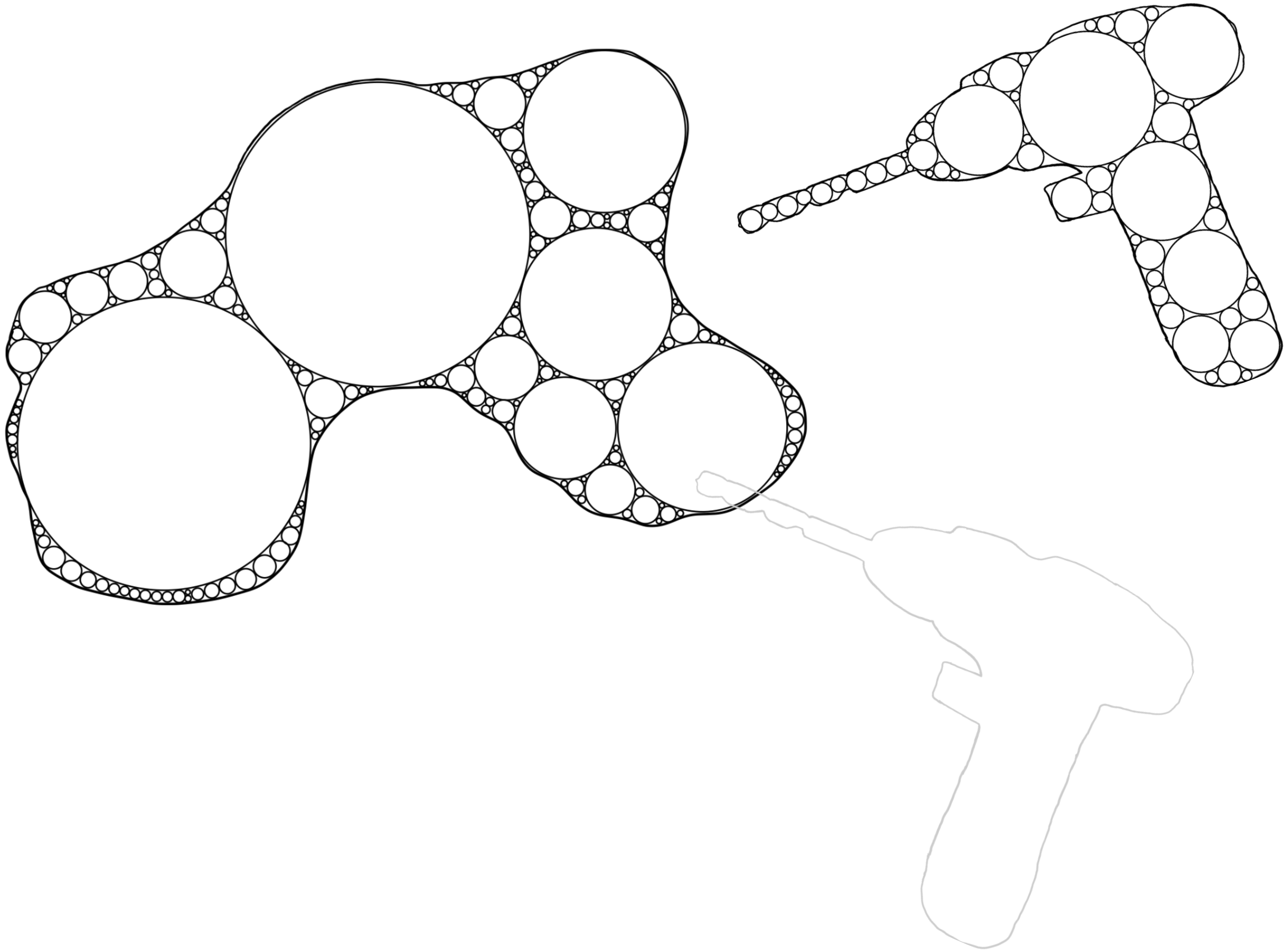
Pop through

Simulation: Physics

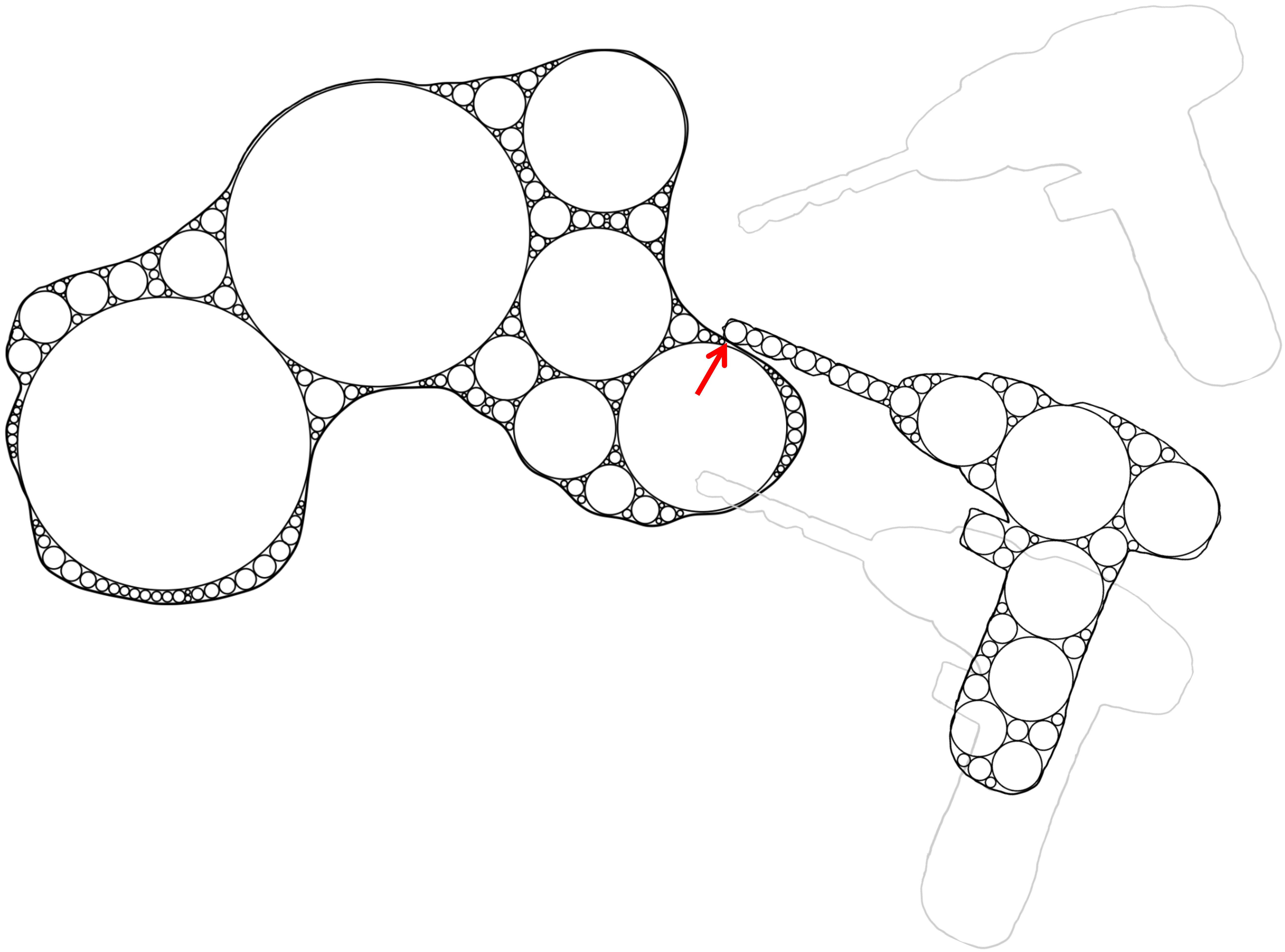


Incorrect contacts

Continuous Collision Detection

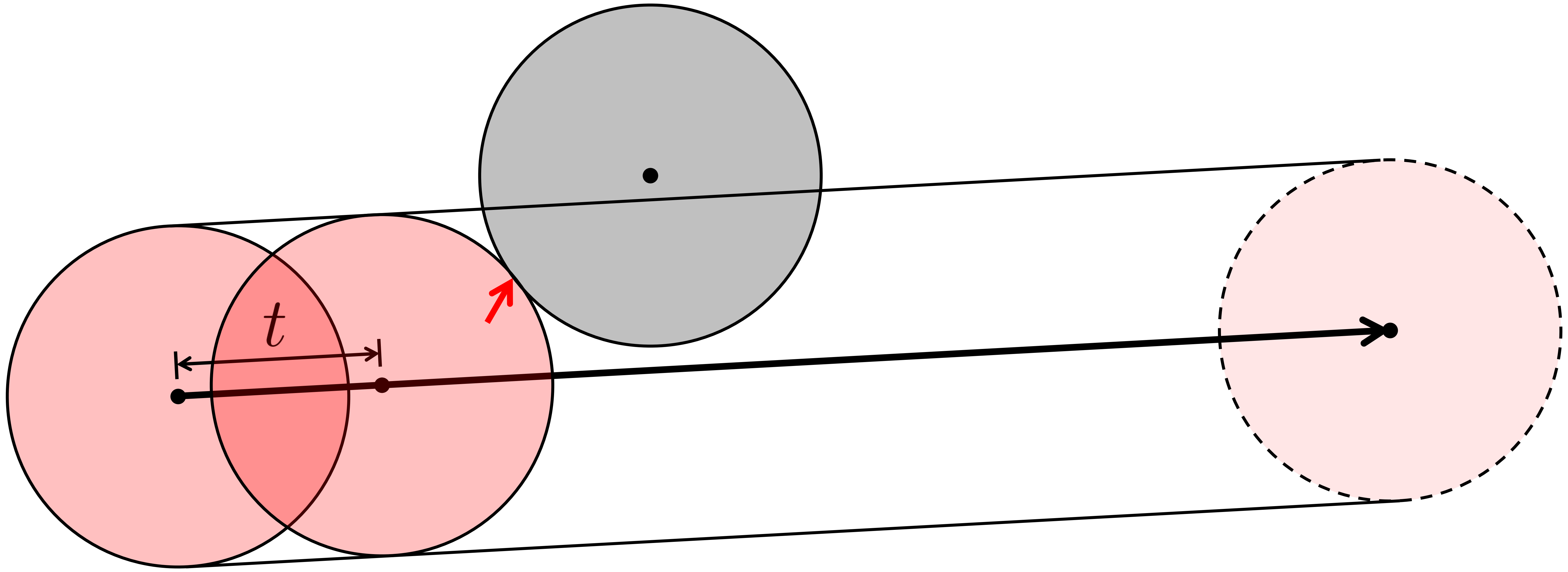


Continuous Collision Detection



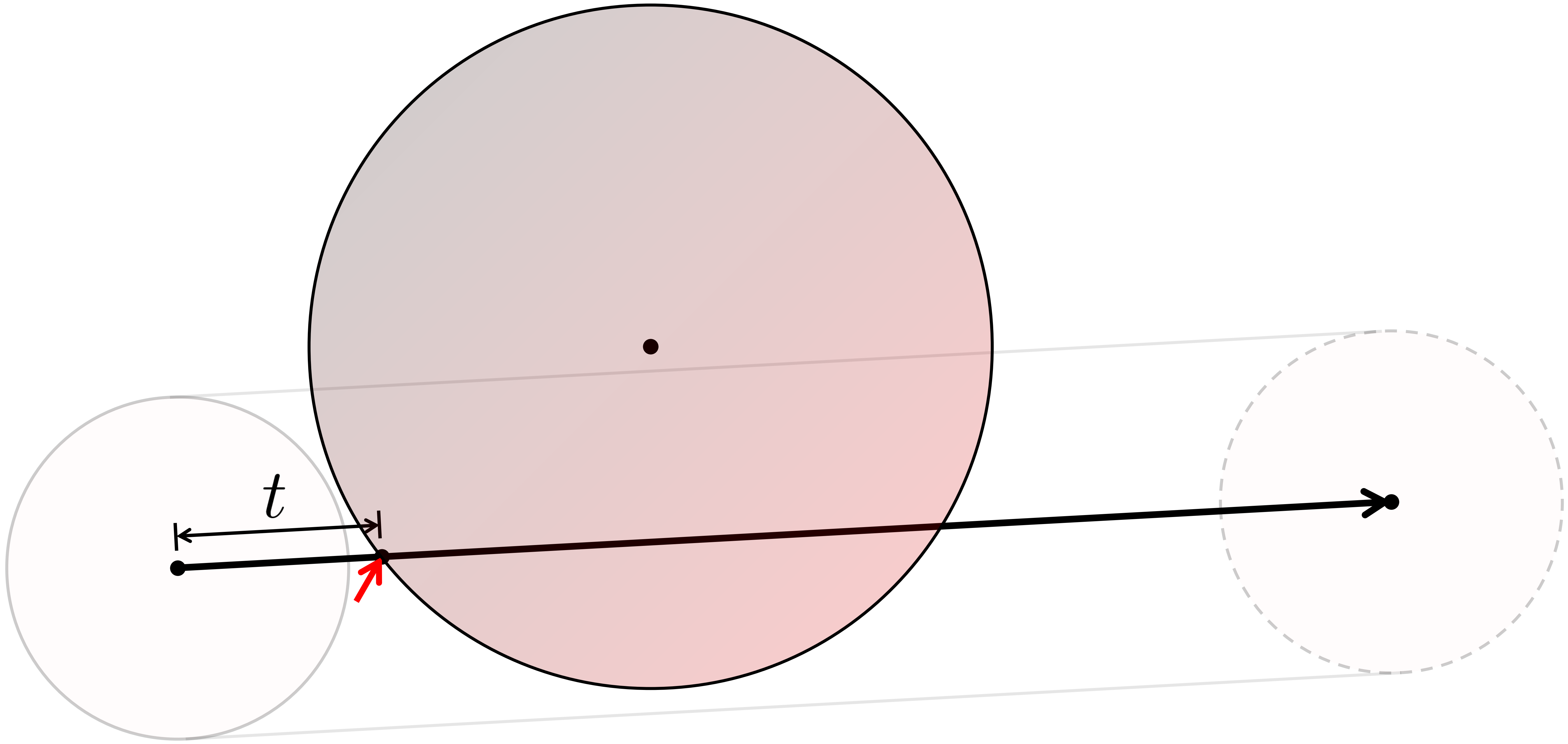
CCD Optimization

- CCD: first contact of swept sphere vs. spheres



CCD Optimization

- CCD: first contact of swept sphere vs. spheres
- Spheres simplify translational CCD to ray vs spheres



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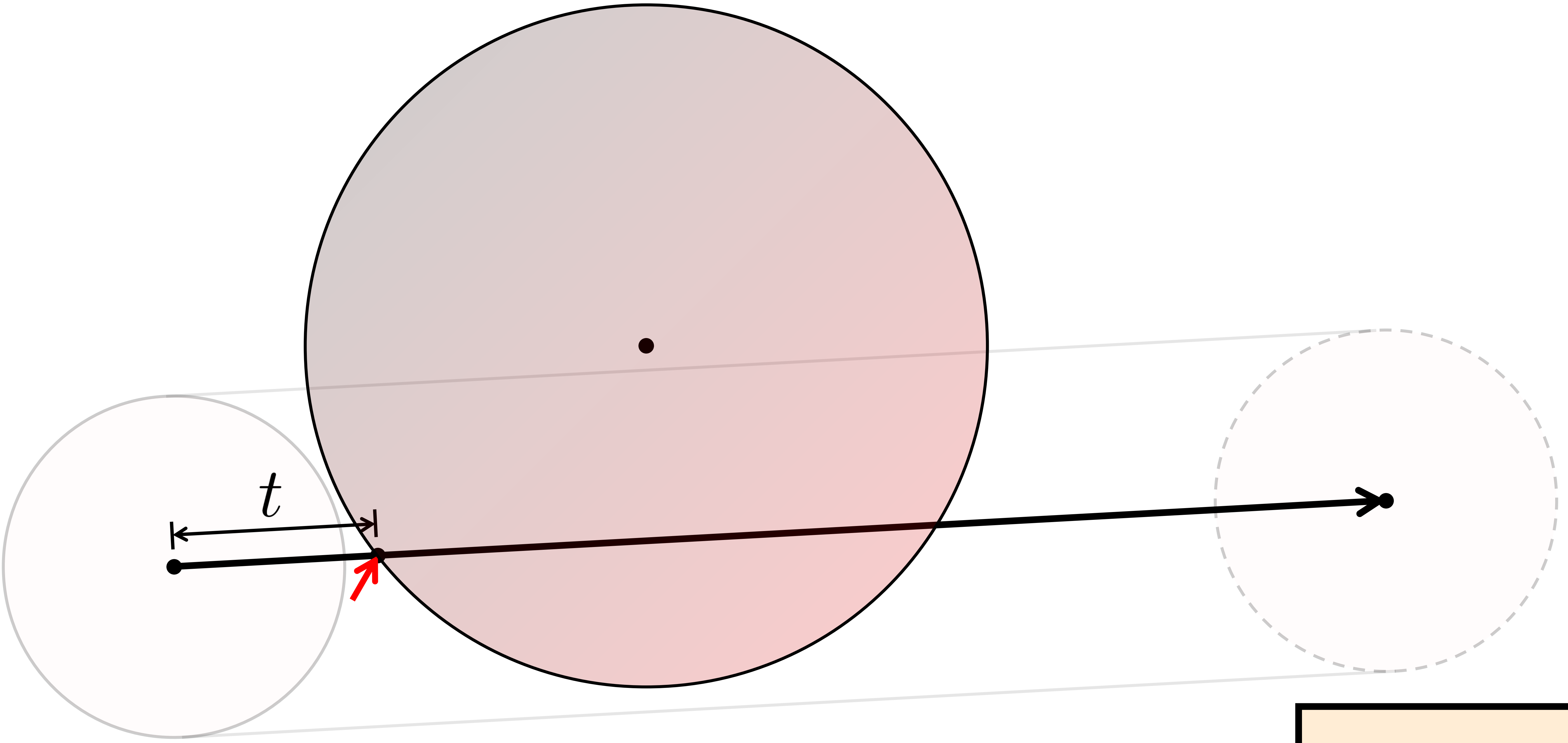
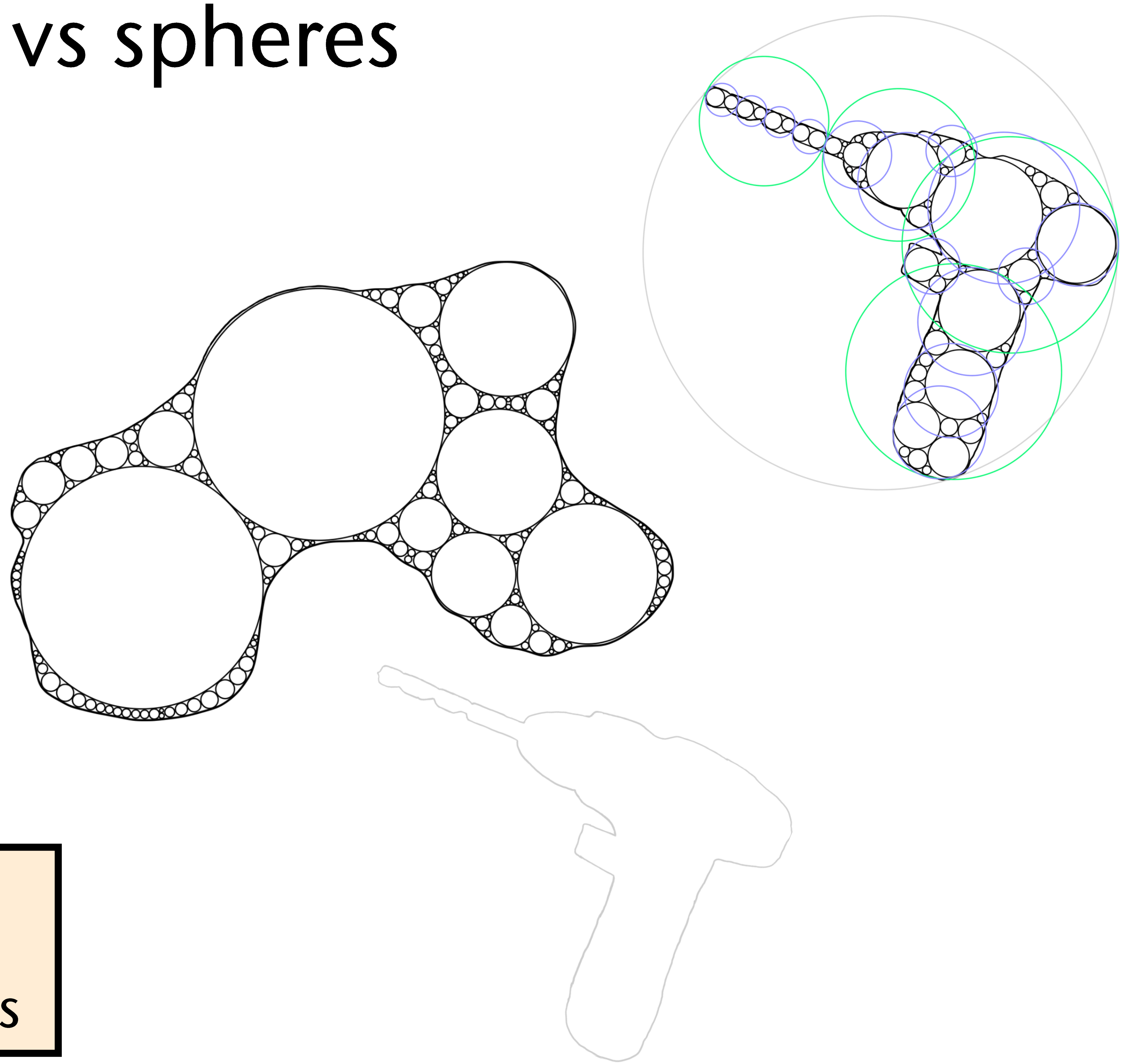
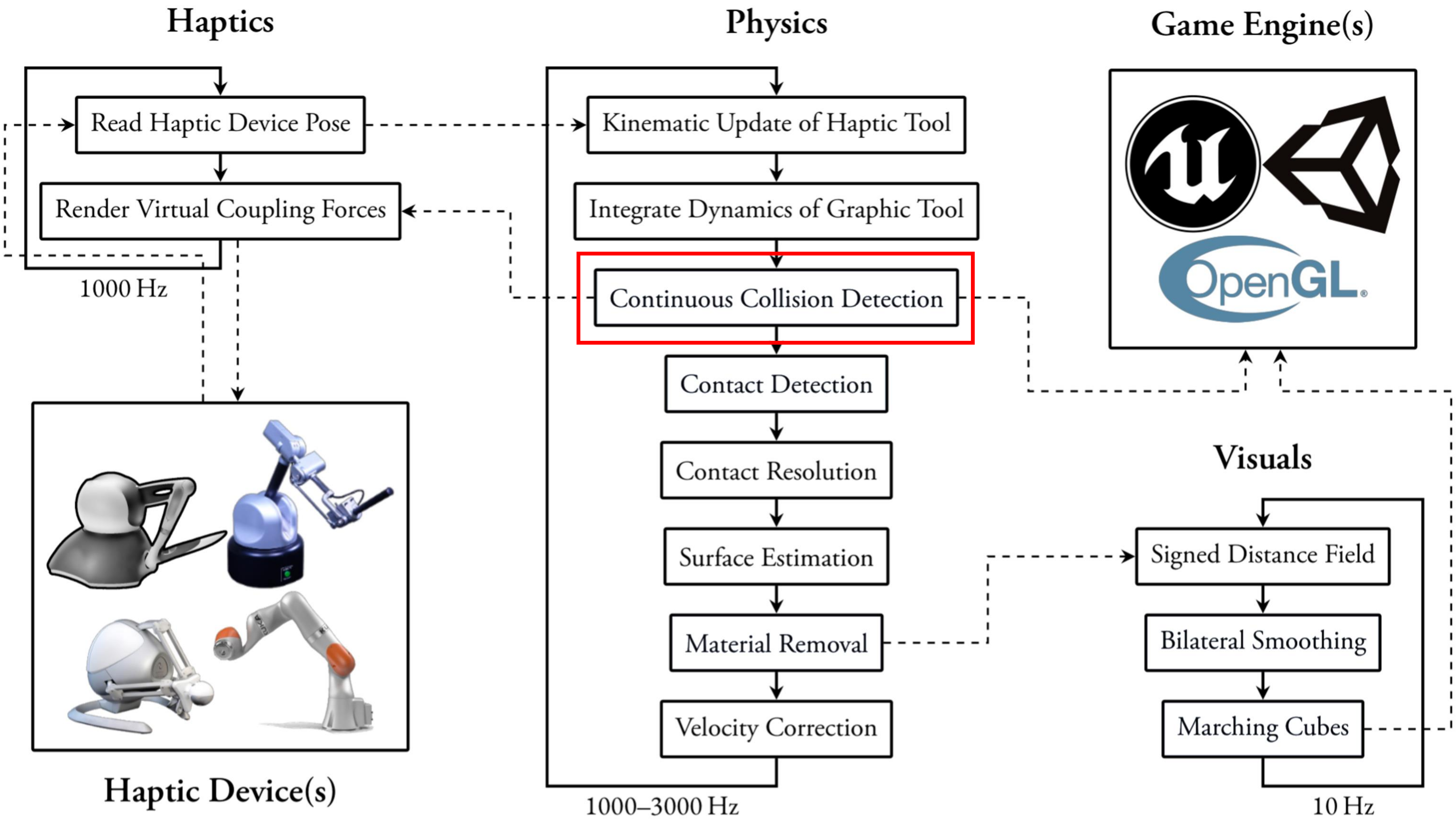




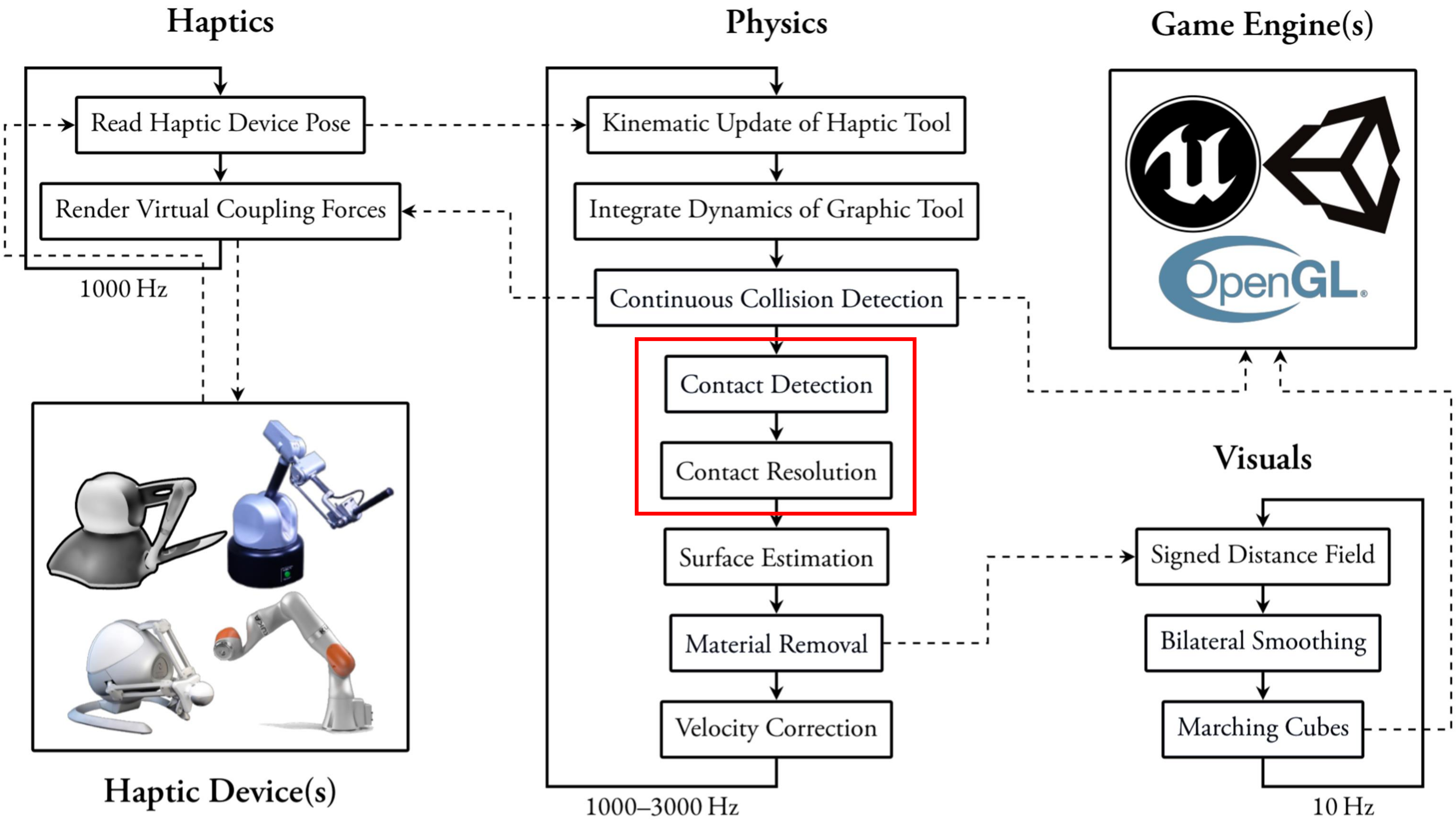
$\sim$ 0.15 ms

100k vs 2k spheres

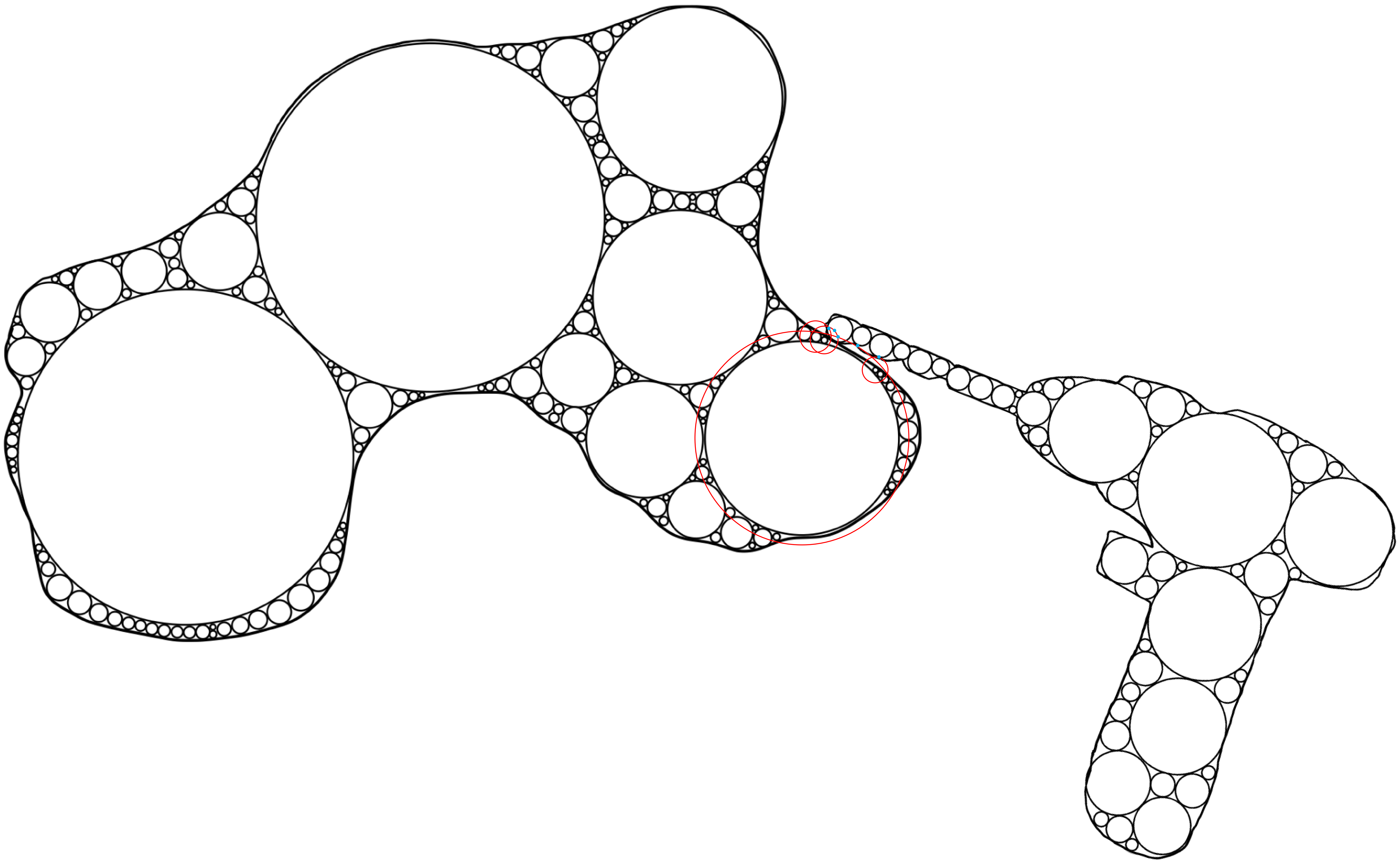
Continuous Collision Detection



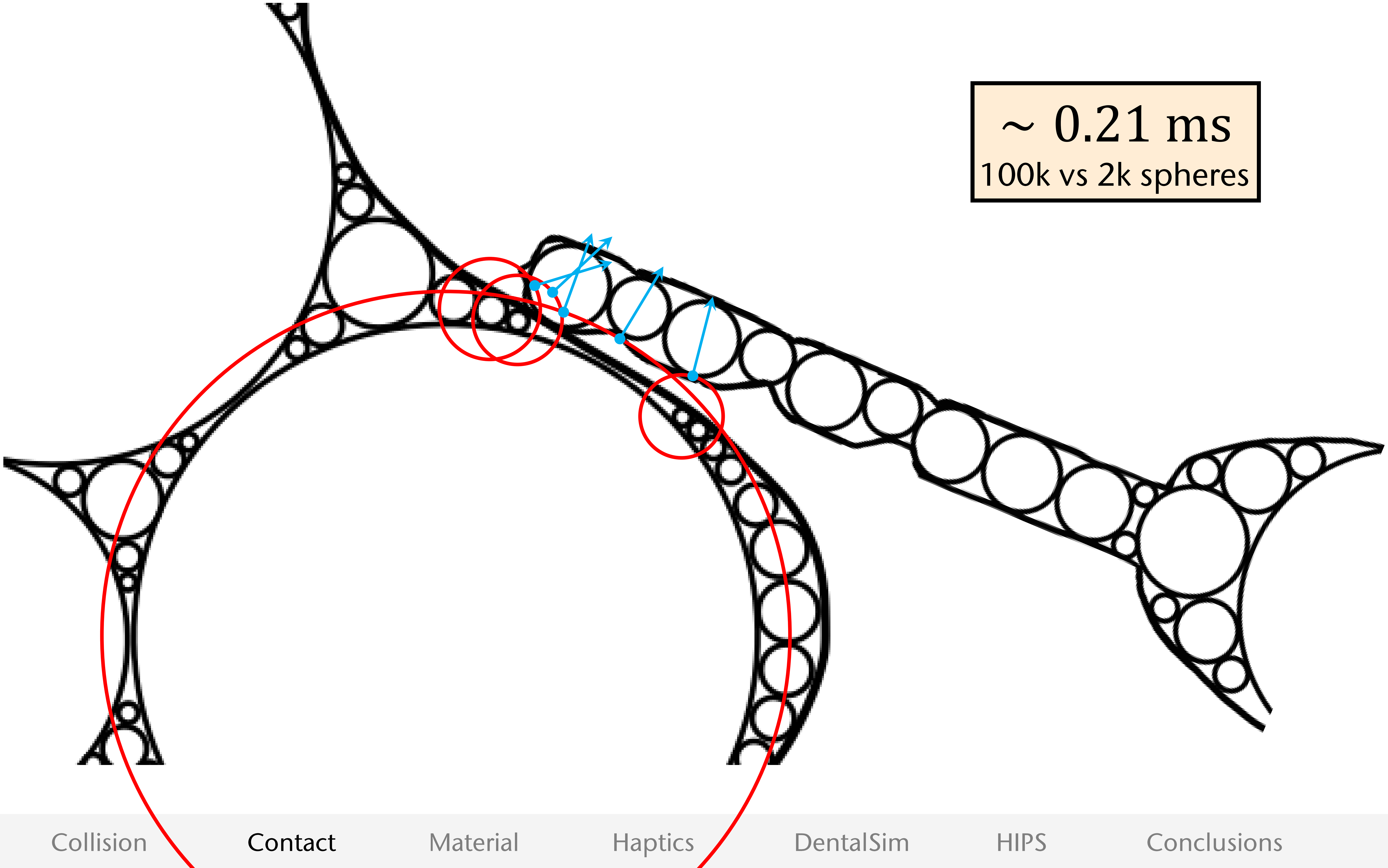
Contact Detection



Multiple Contacts without Overlap



Multiple Contacts without Overlap



~ 0.21 ms
100k vs 2k spheres

Contact Resolution

Directly enforced | Indirectly enforced

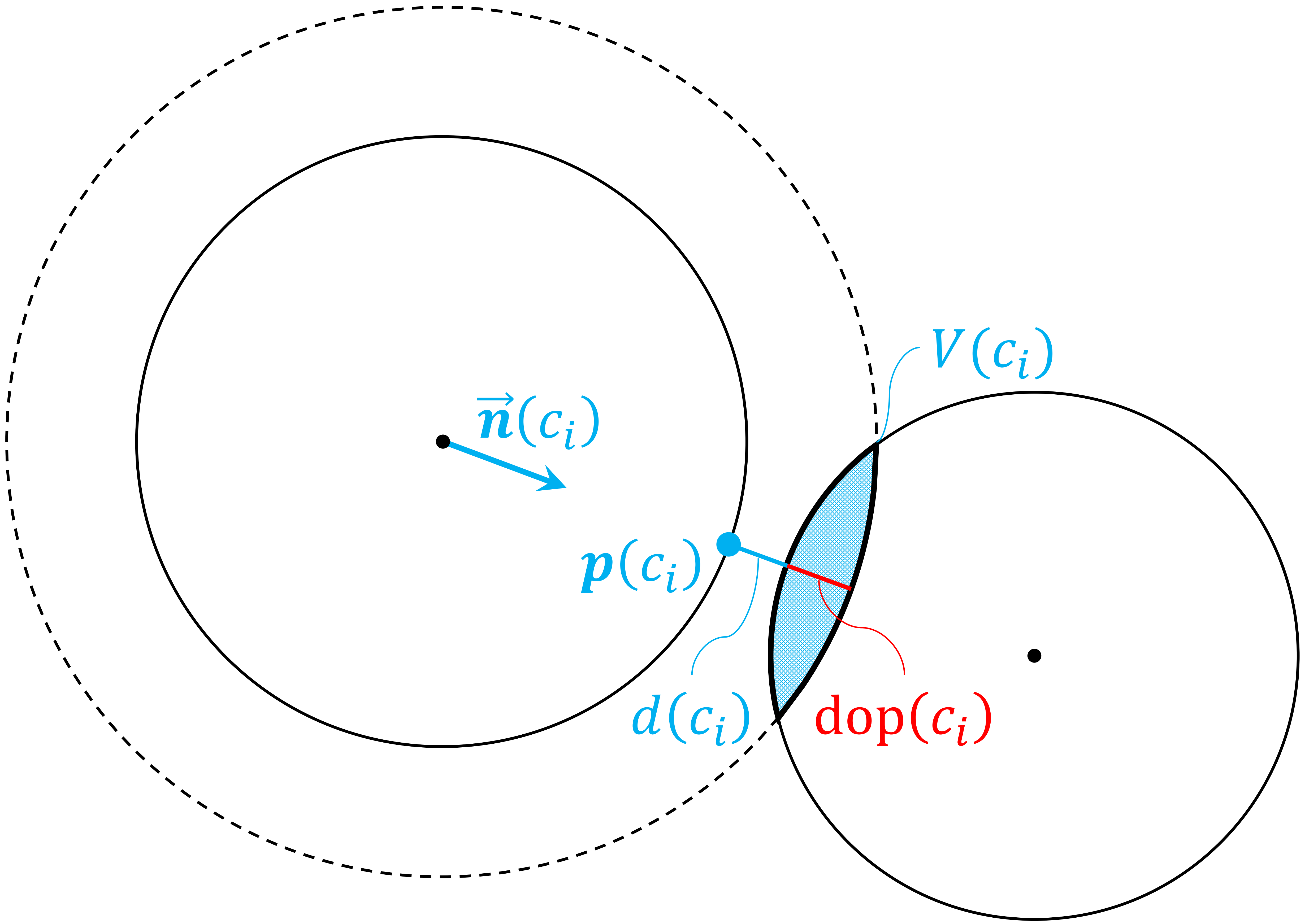
Constraint-based

Impulse-based

Position-based

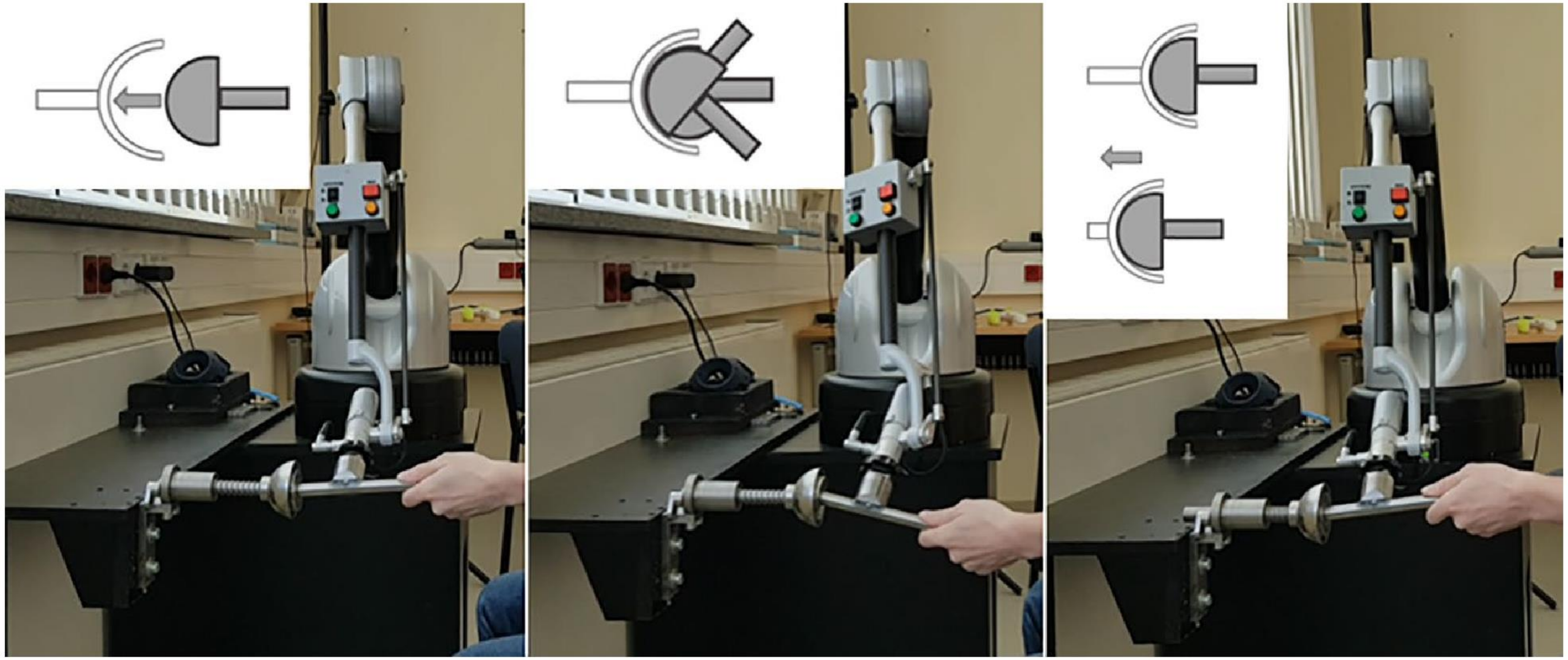
Penalty-based

Slow running time | Fast running time



Haptic Rendering of Large Forces

- Abstracted three task from hip reaming
  - Worst case: steel on steel
- Rendering methods: penalty, impulse, rigid-body, constraint



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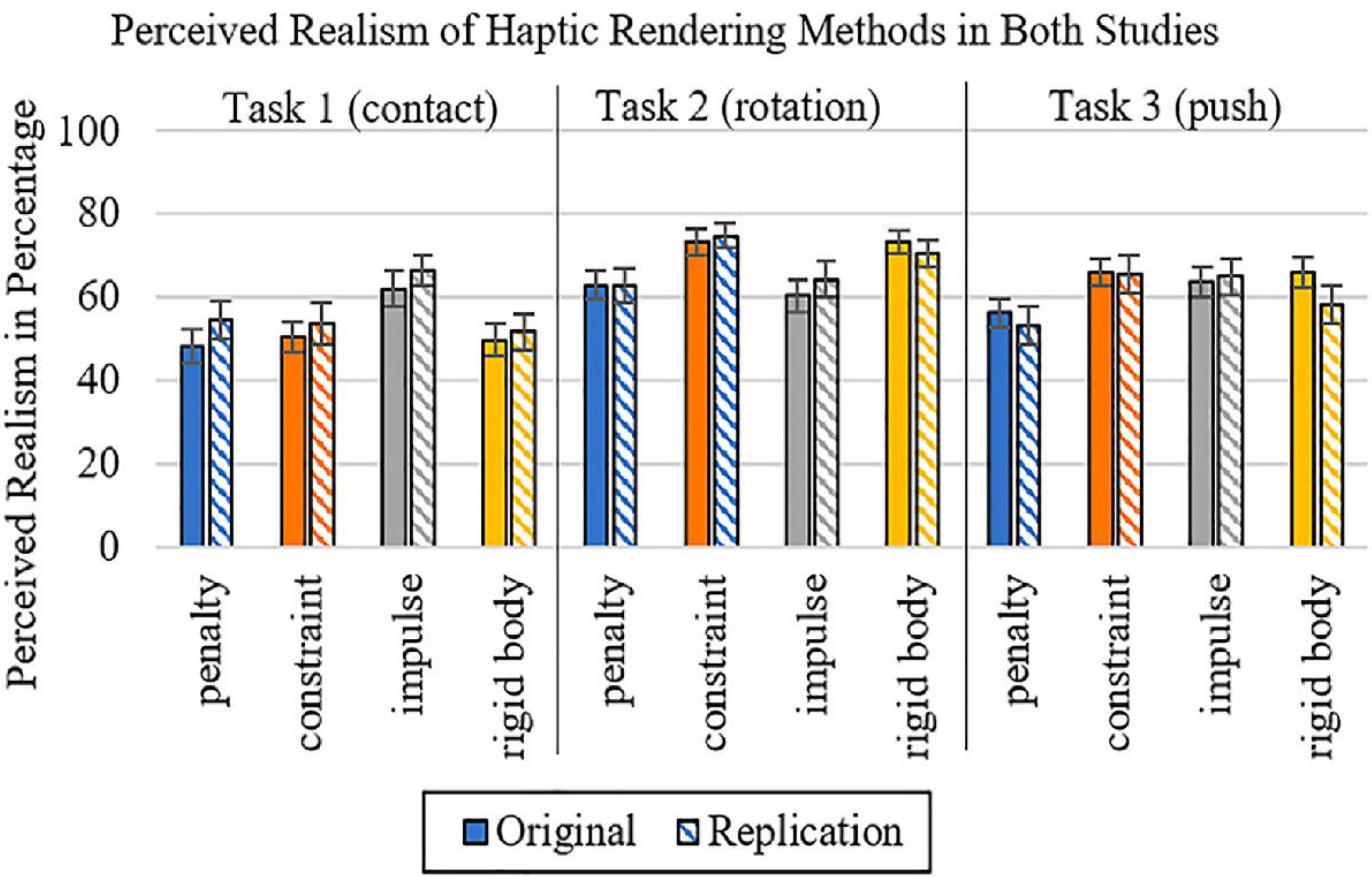
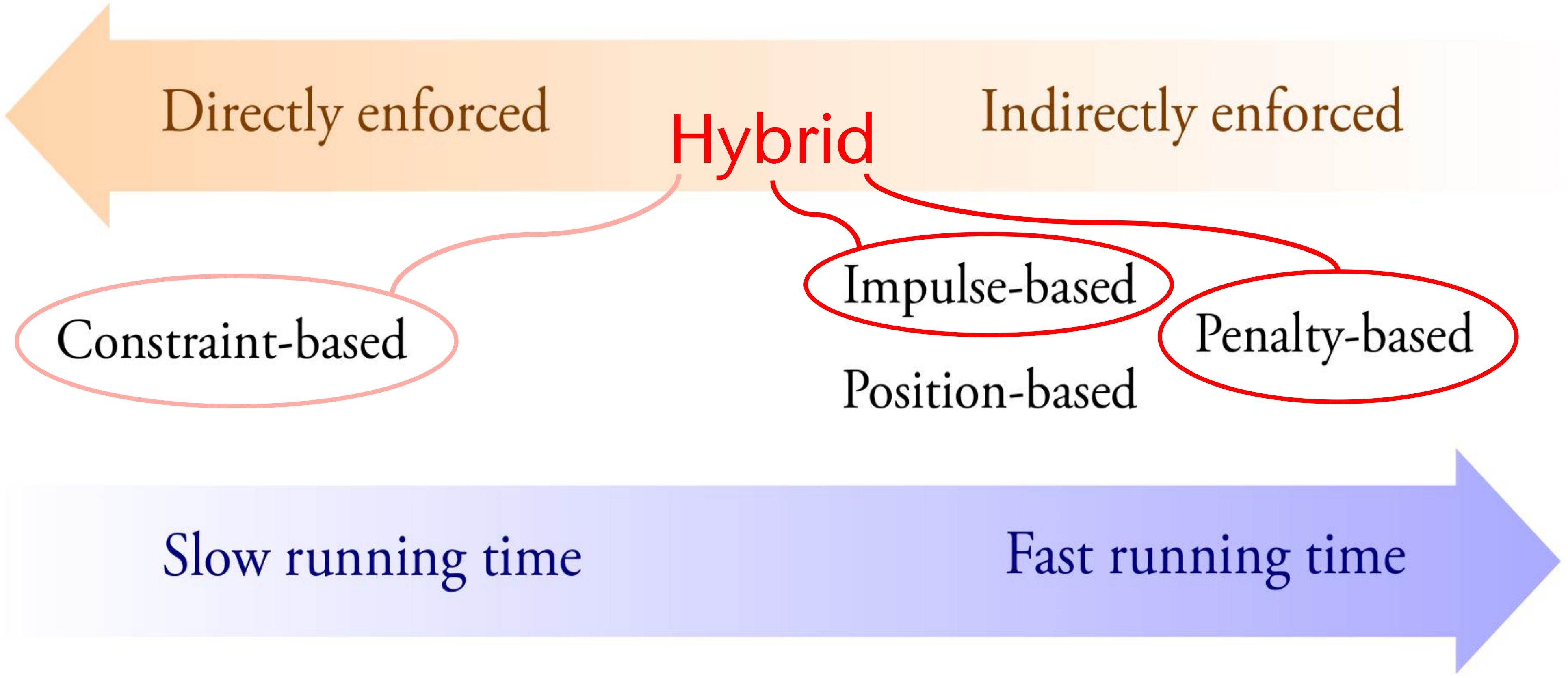
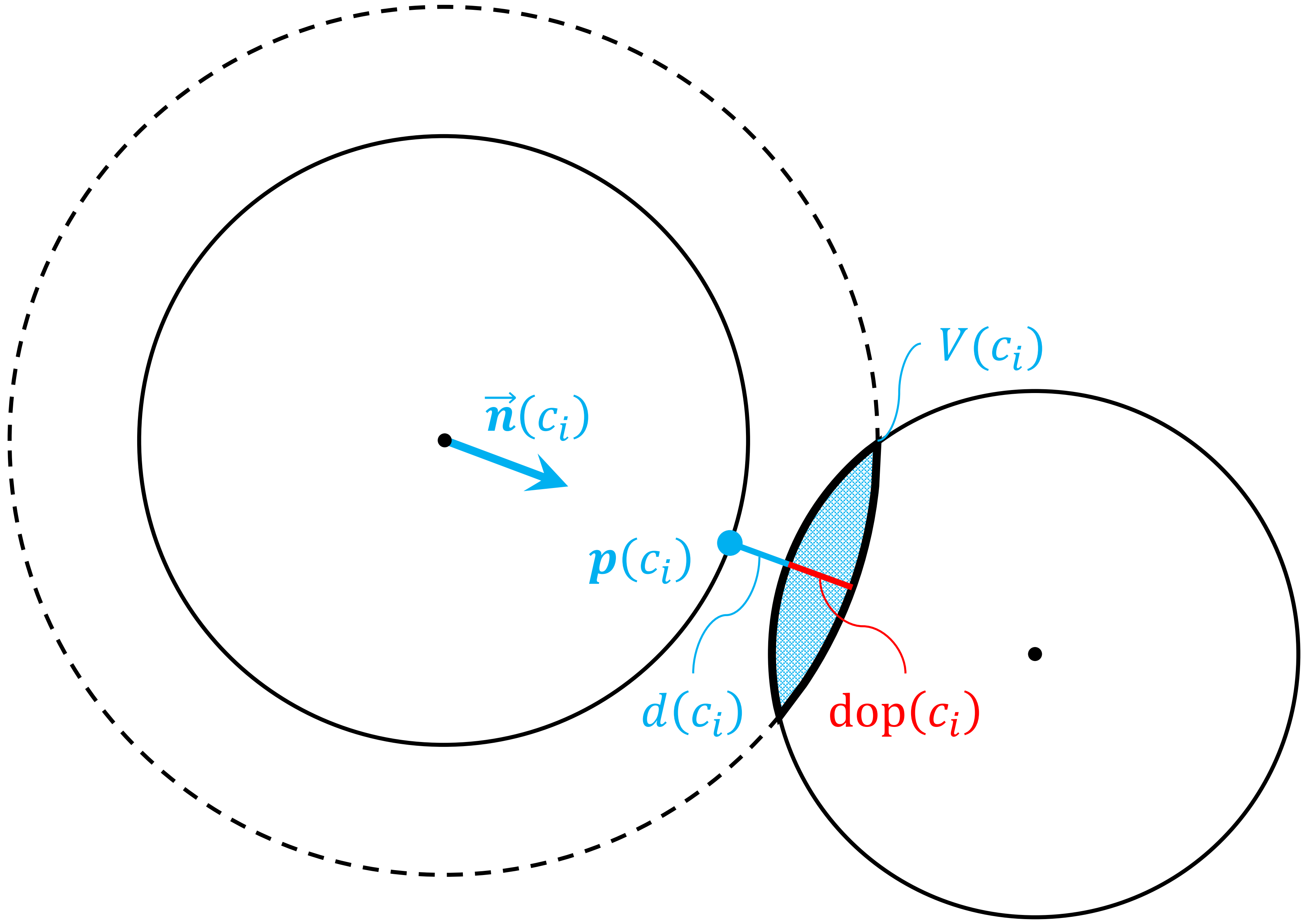


Hybrid Contact Resolution Approach



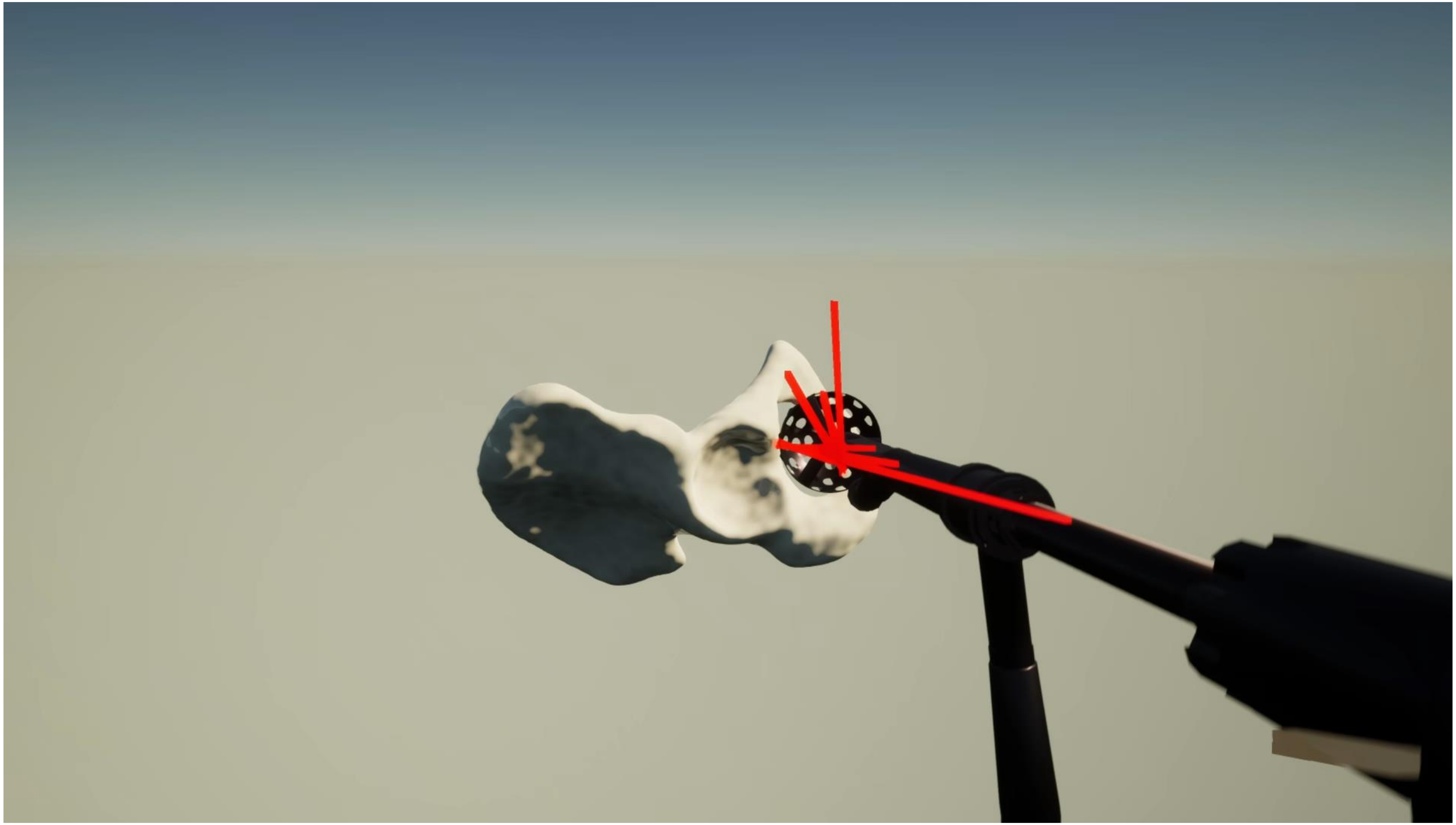


- Colliding contacts have velocity *constraints*
  - Iteratively apply partial *impulses* with friction
- Resting contacts resolved using *penalty* force

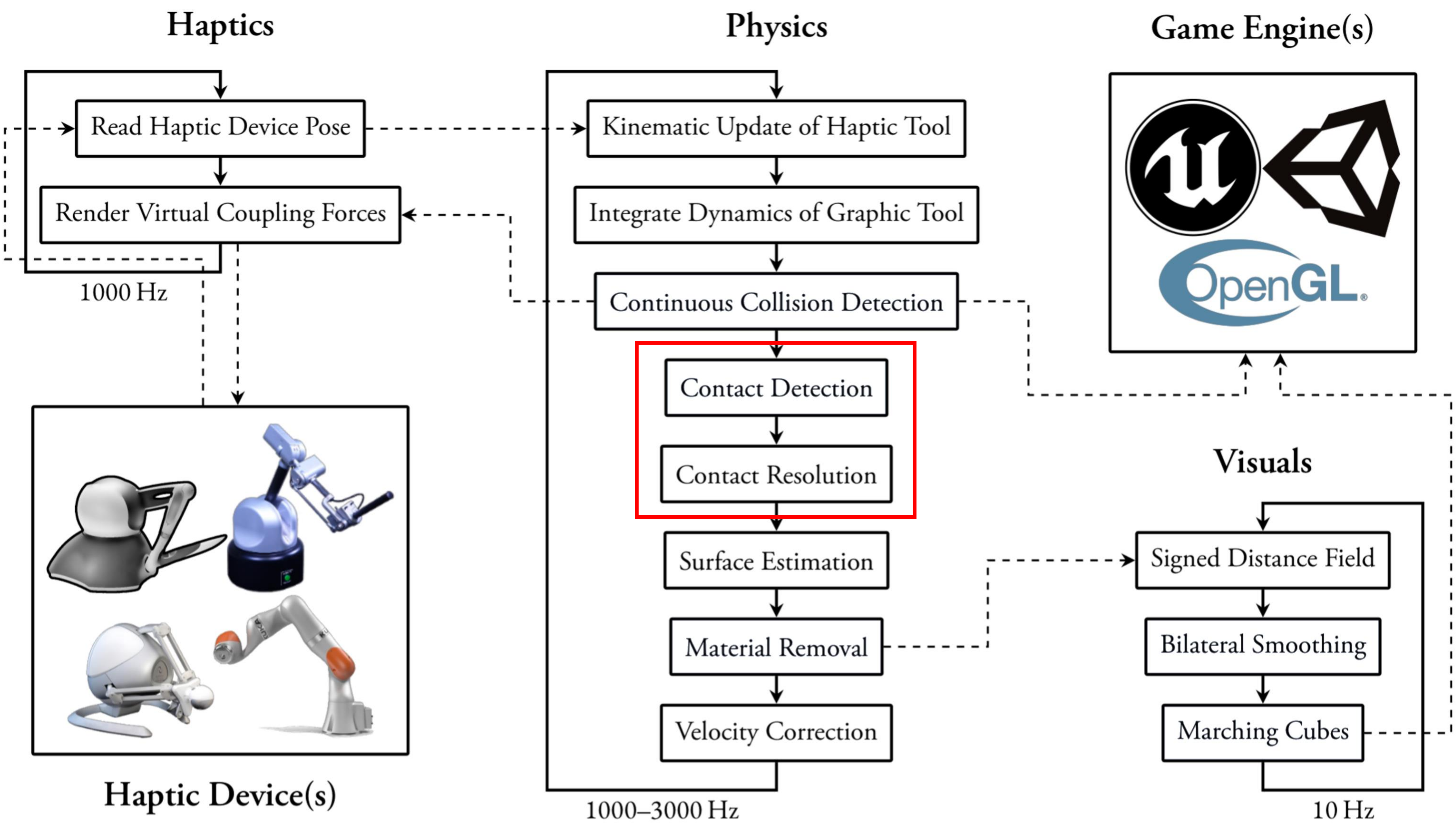
$$\vec{j}_i^{\,n} = \frac{1}{N} \frac{-(1+e)\dot{\boldsymbol{p}}(c_i)}{\vec{\boldsymbol{n}}(c_i)^T \left(\boldsymbol{I}^{-1}\left[(\vec{\boldsymbol{r}}(c_i) \times \vec{\boldsymbol{n}}(c_i)) \times \vec{\boldsymbol{r}}(c_i)\right]\right)}$$

$$\vec{\boldsymbol{f}}(c_i) = V(c_i)\vec{\boldsymbol{n}}(c_i)k_c$$

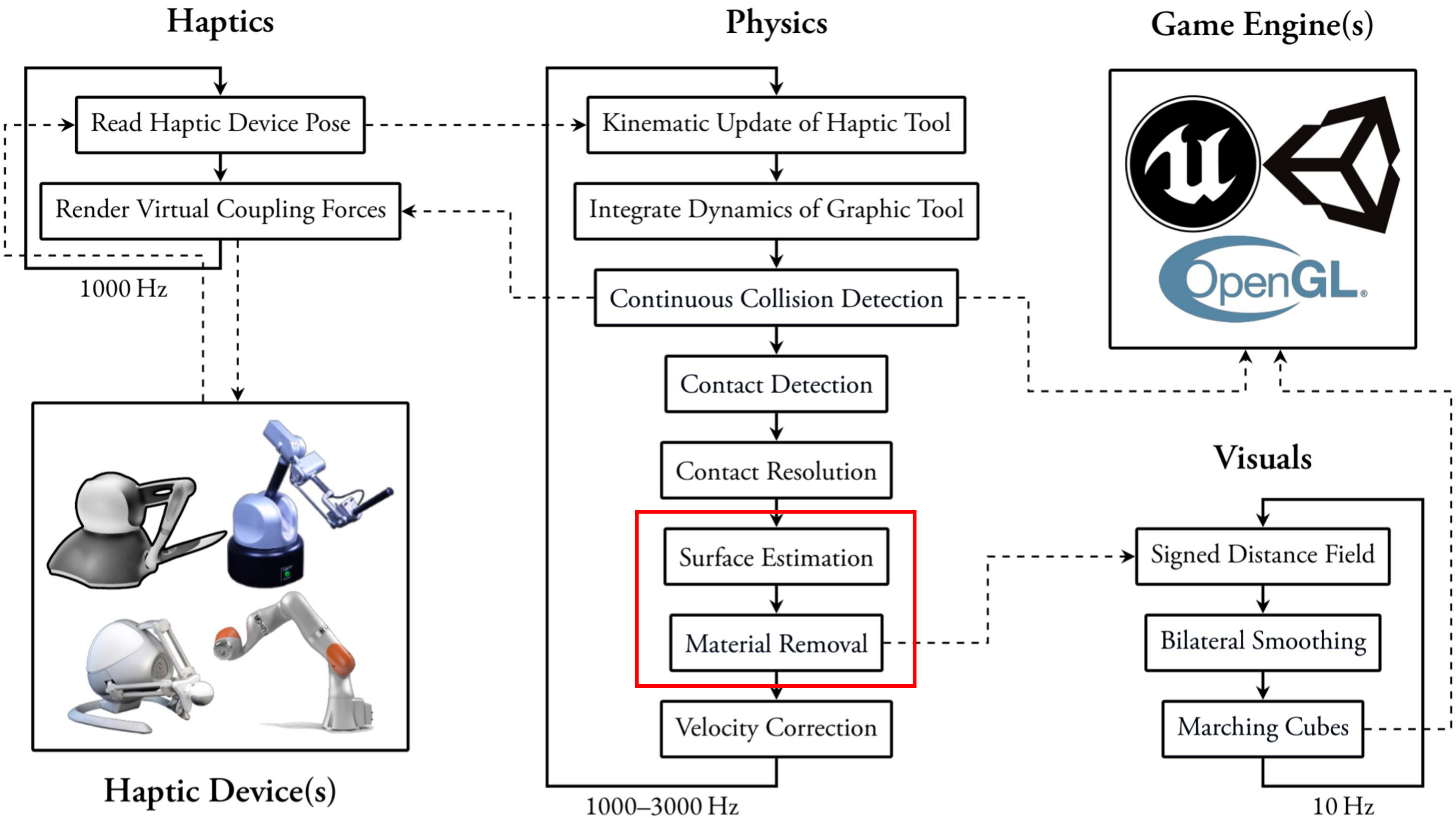
Contact Resolution Approach



Simulation: Contact Resolution

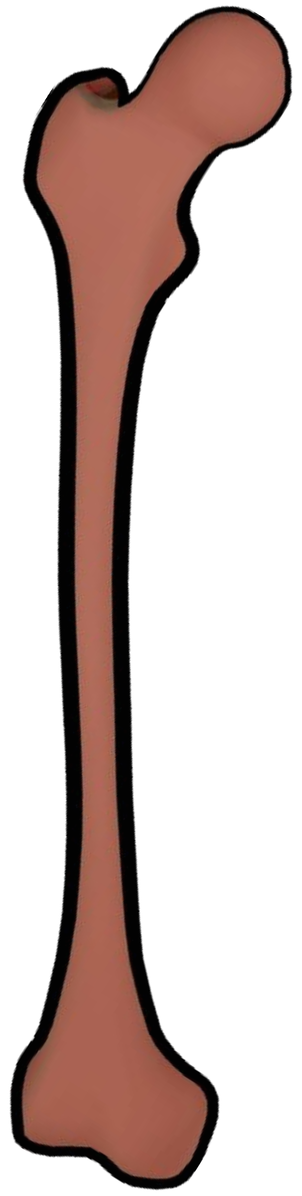


Simulation: Surface Estimation & Materials



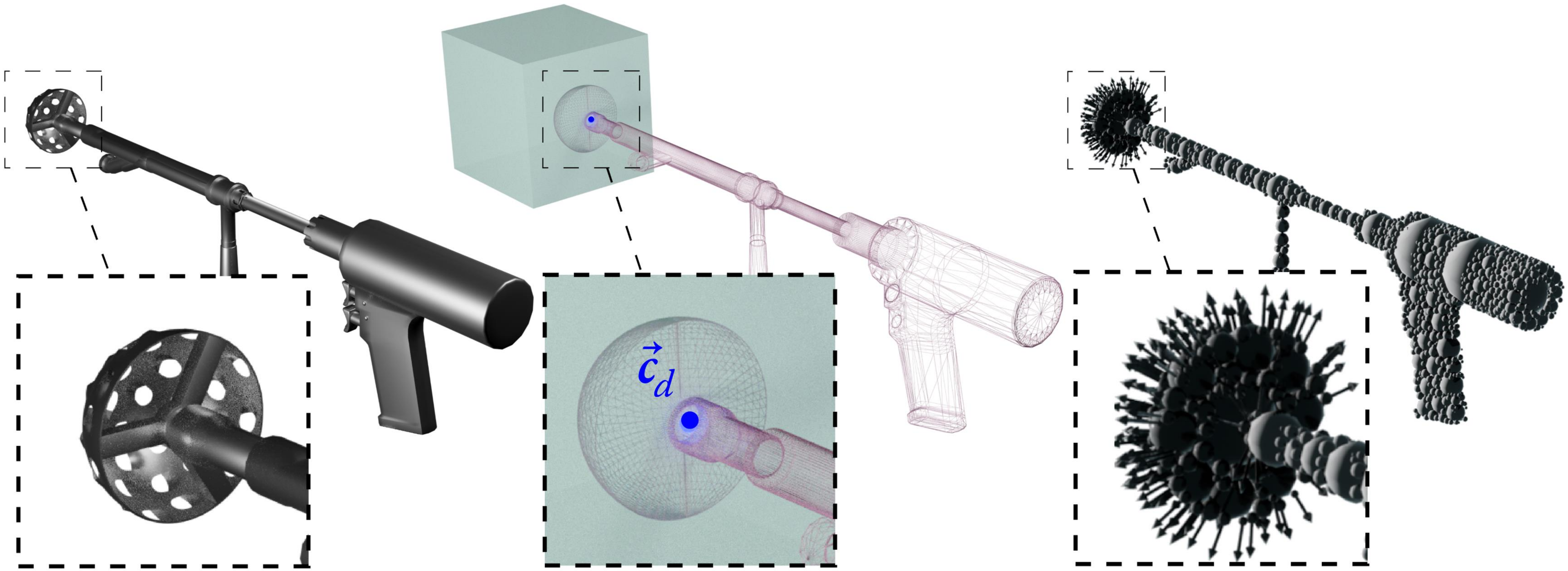
Material Removal

- Modulate tool feed rate based on following:
  1. Applied pressure by the user
  2. Cutting contact area
  3. Local material density (tooth layers, cortical bone)

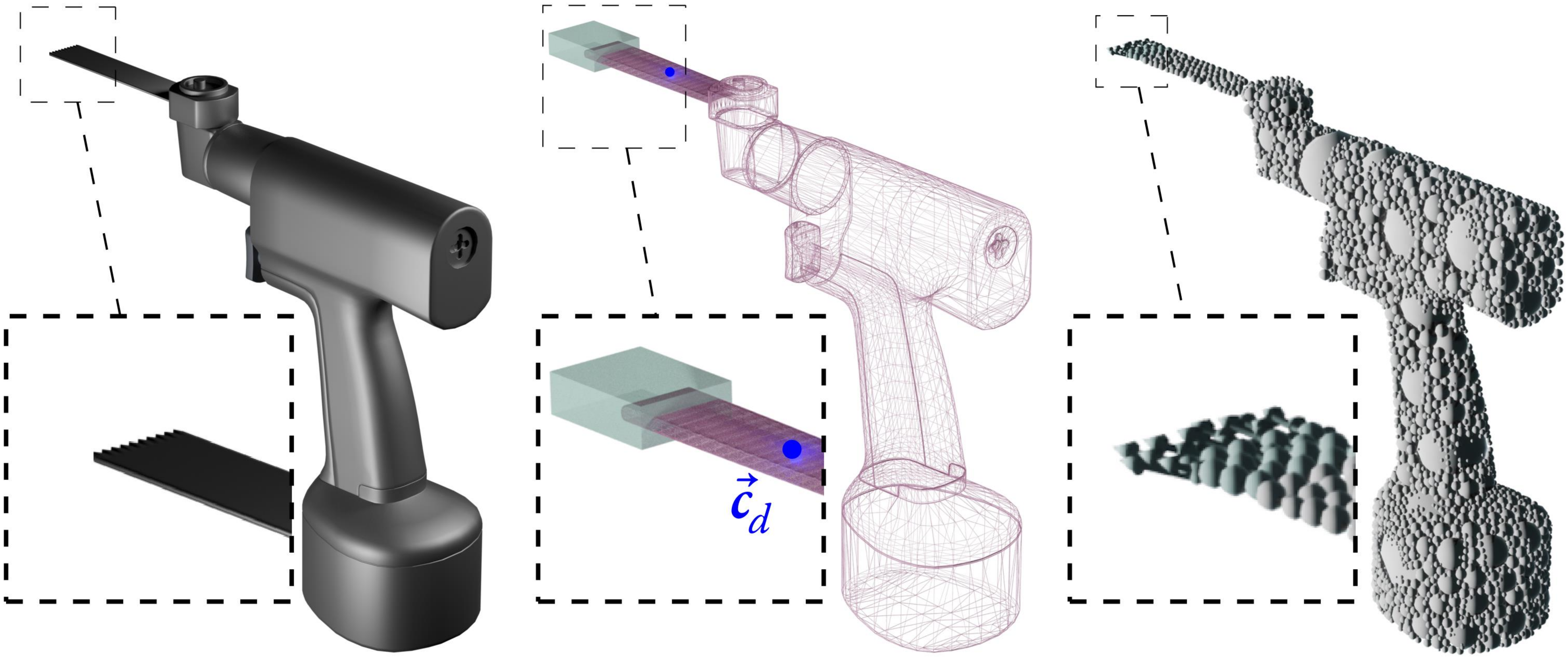


- Cutting model
  - Define feed rates $r_d^{\mathrm{ref}}, r_d^{\max}$ per tool (for reference and max. pressure)
  - Modulate r_d by *local* pressure: $|f_s + \tau_s \times \vec{\boldsymbol{r}}_i|$
  - Modulate r_d by *global* contact volume (density scaled), inversely

Material Removal



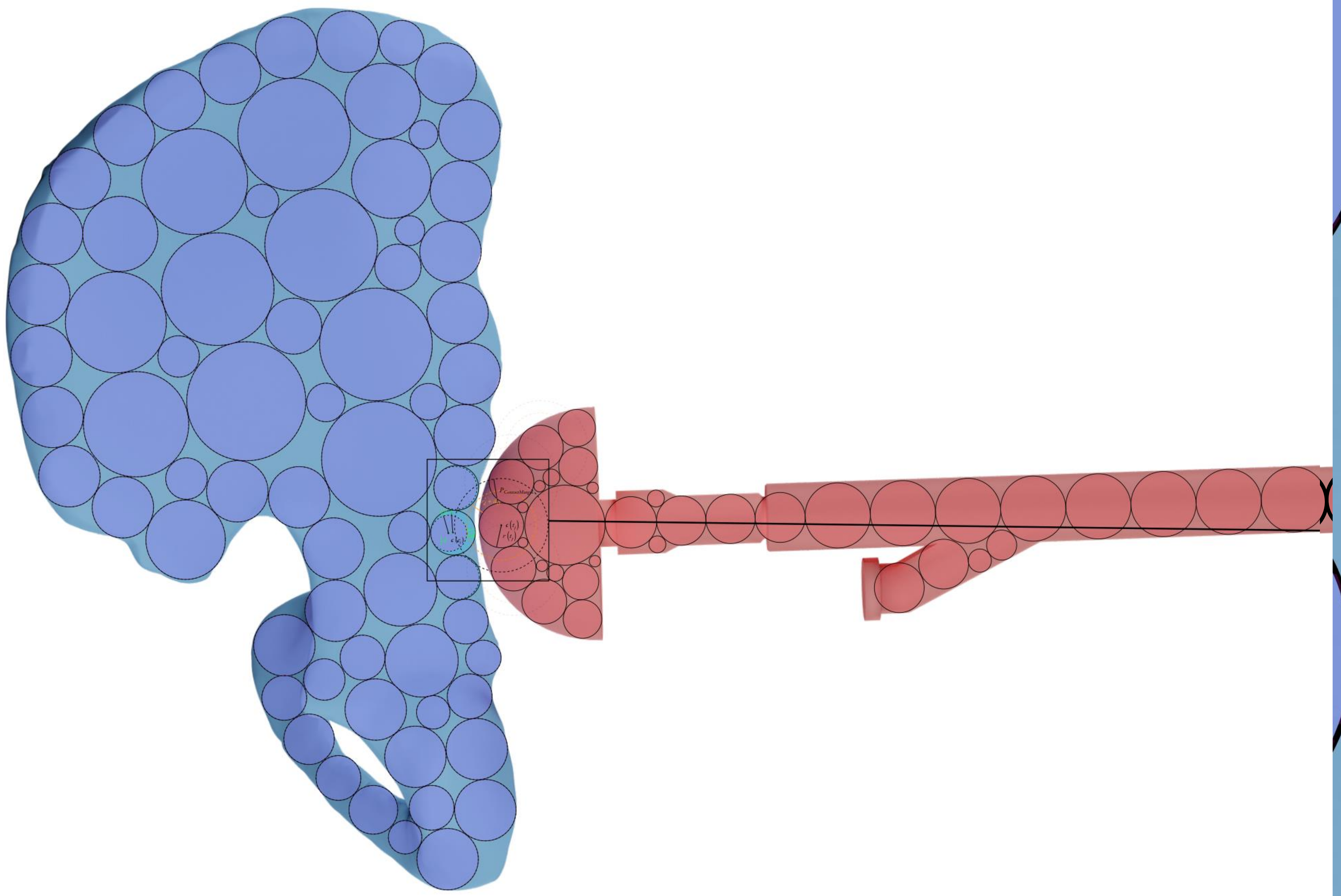
Material Removal (Cutting Direction)

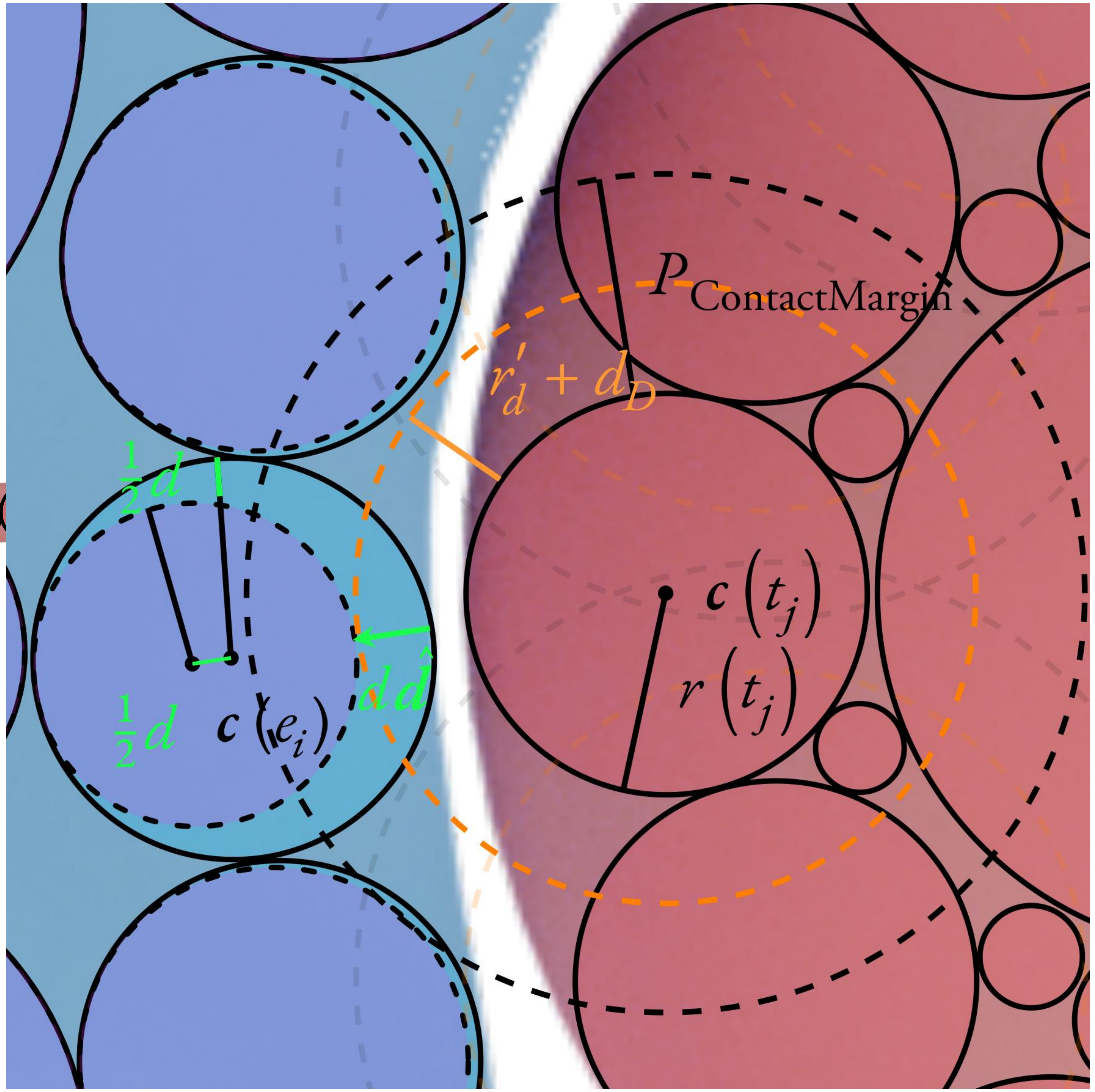


Material Removal (Cutting Direction)

- Modulate *per contact* by angle of normal & drill direction

Stepless Material Removal





Material Removal: What About Friction?

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- Drilling friction
  - Increase point velocity during tangential impulse solve

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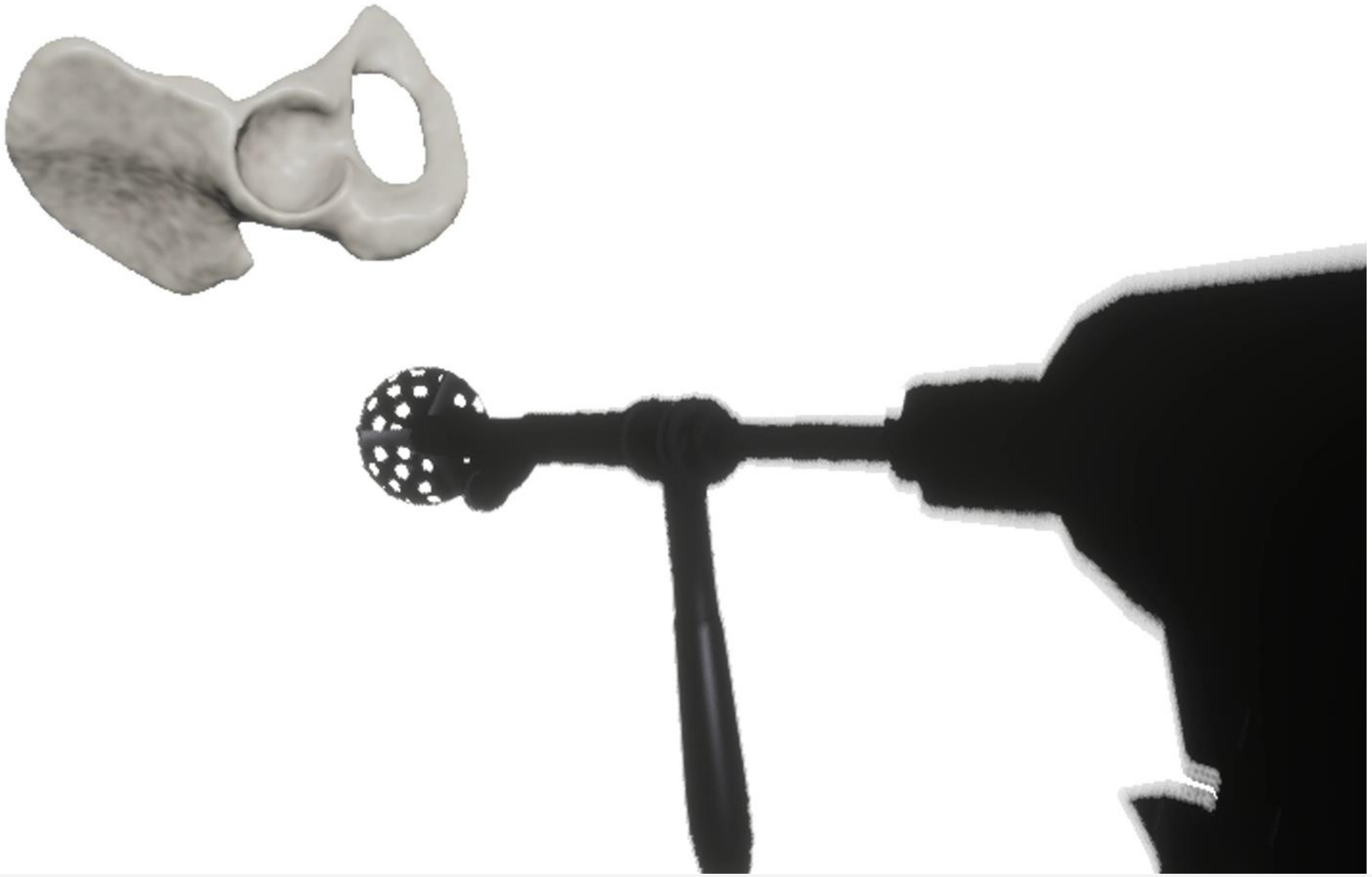
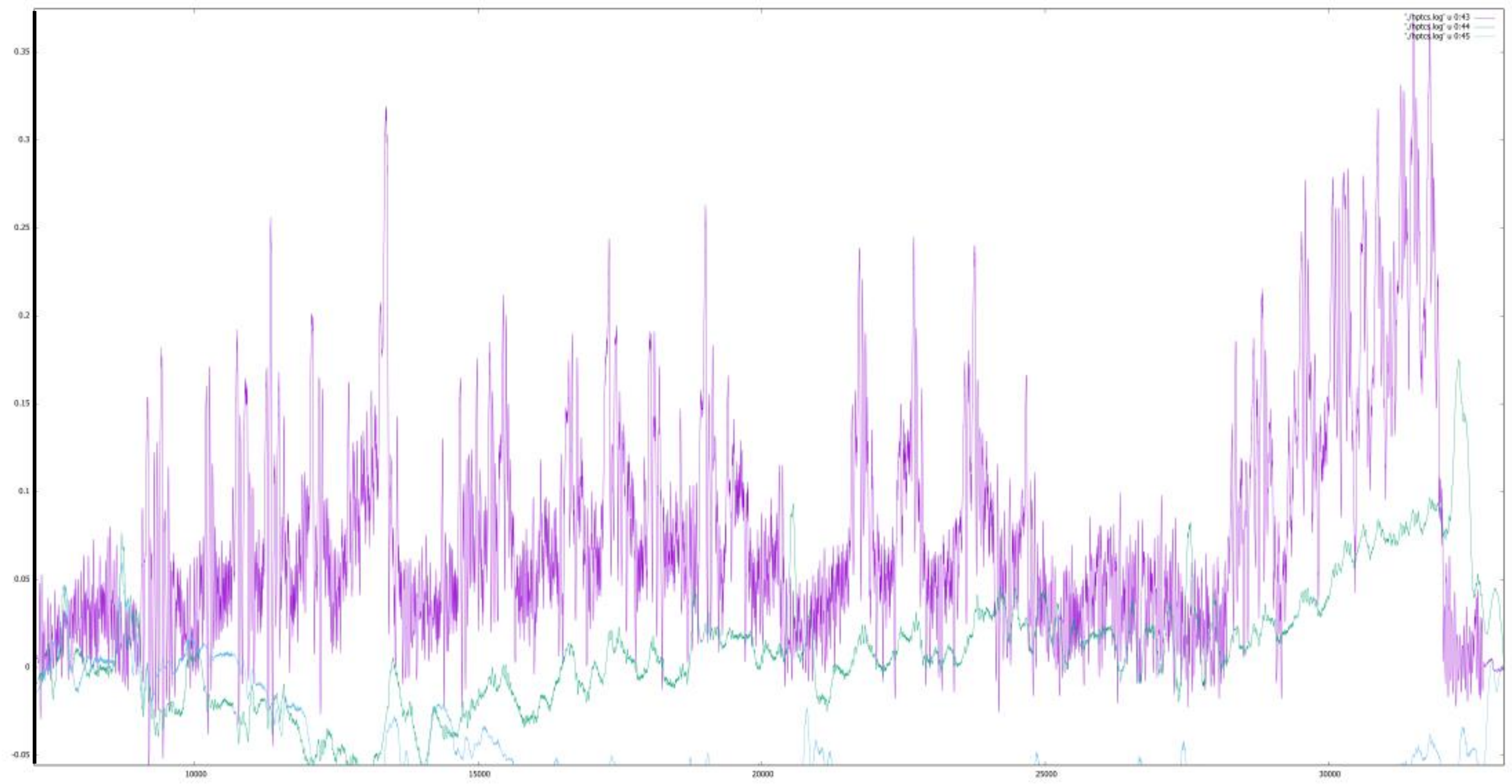
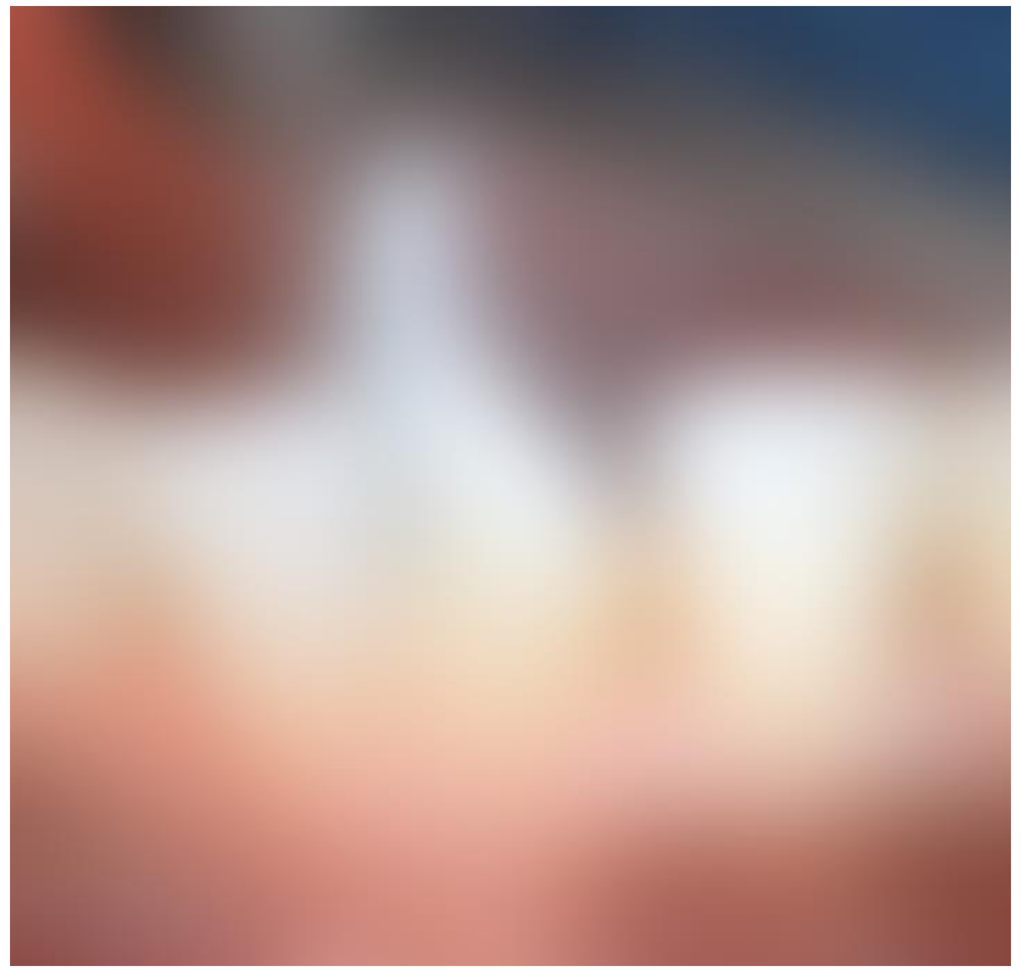
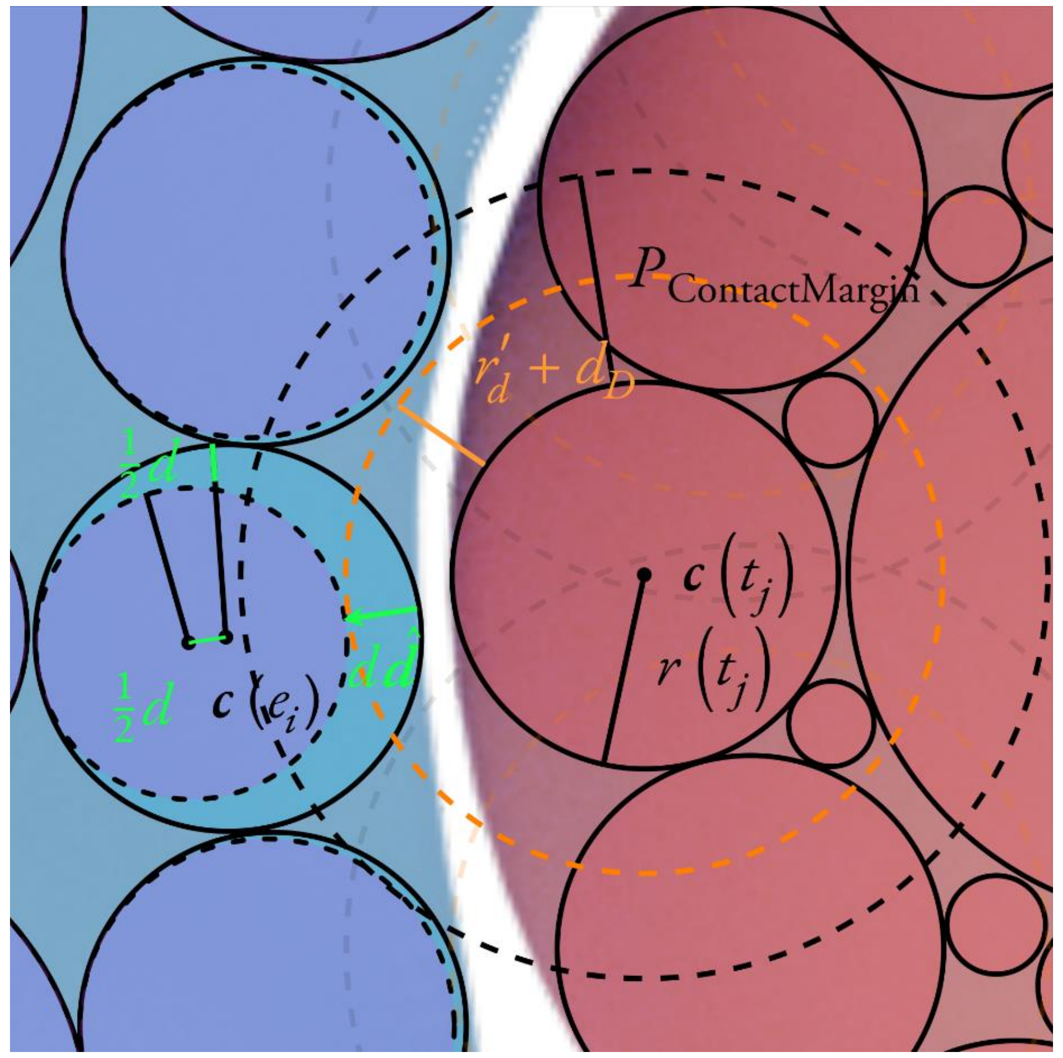


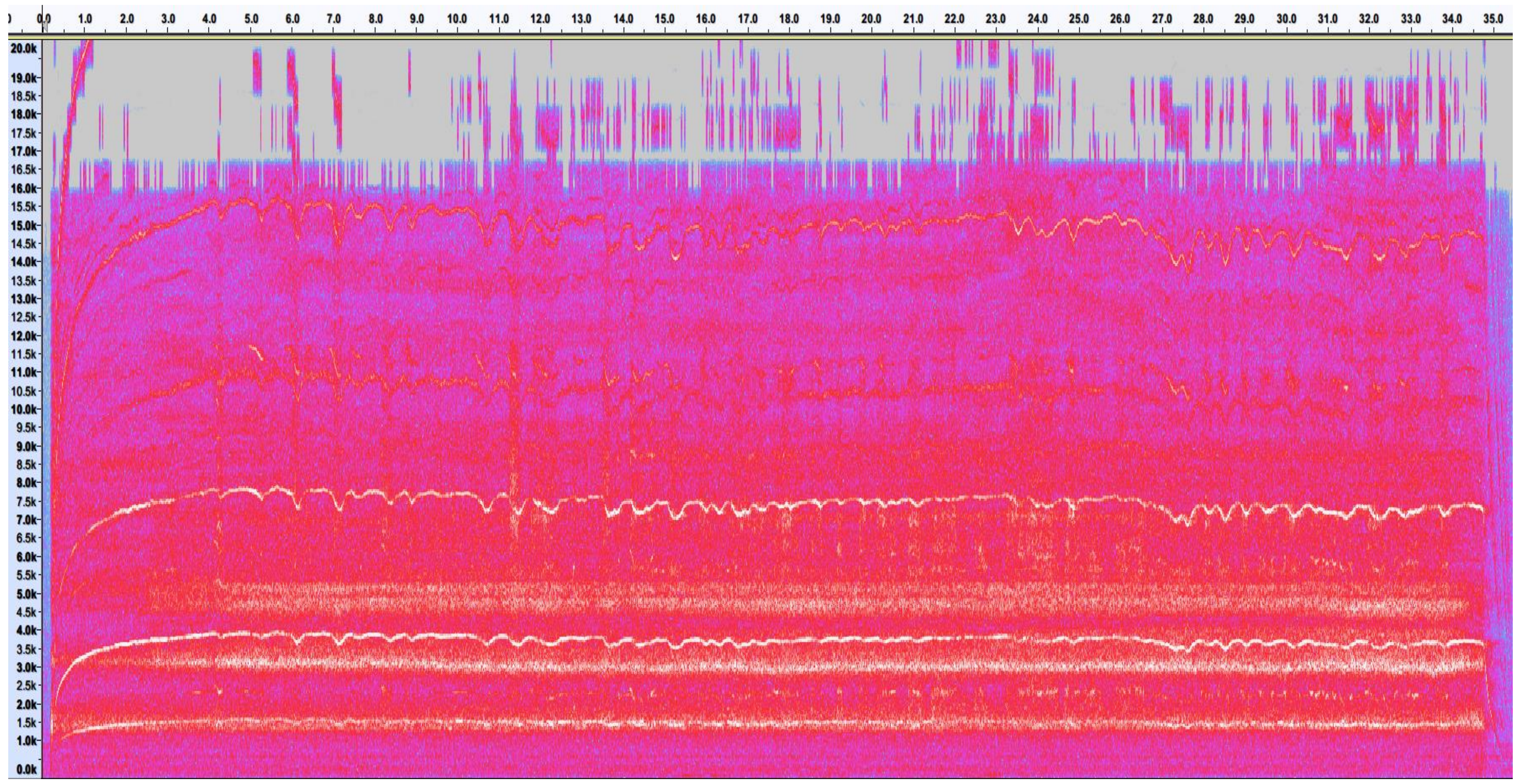


Tool Sounds

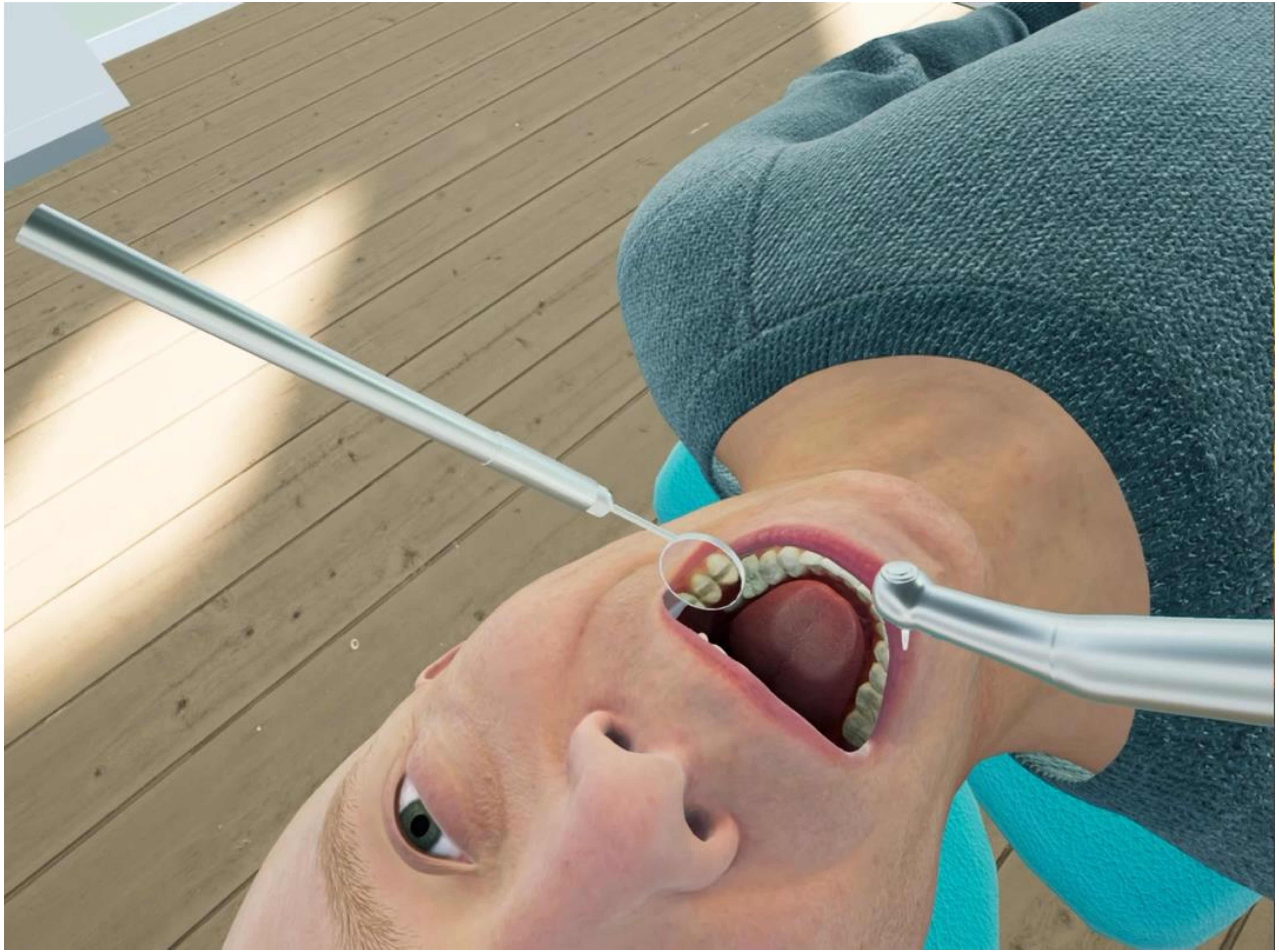
- Increase immersion and realism of drilling
- Drilling tools have a distinct sound signature
- Frequency response modulation based on
  1. Motor rotation speed
  2. Cutting resistance



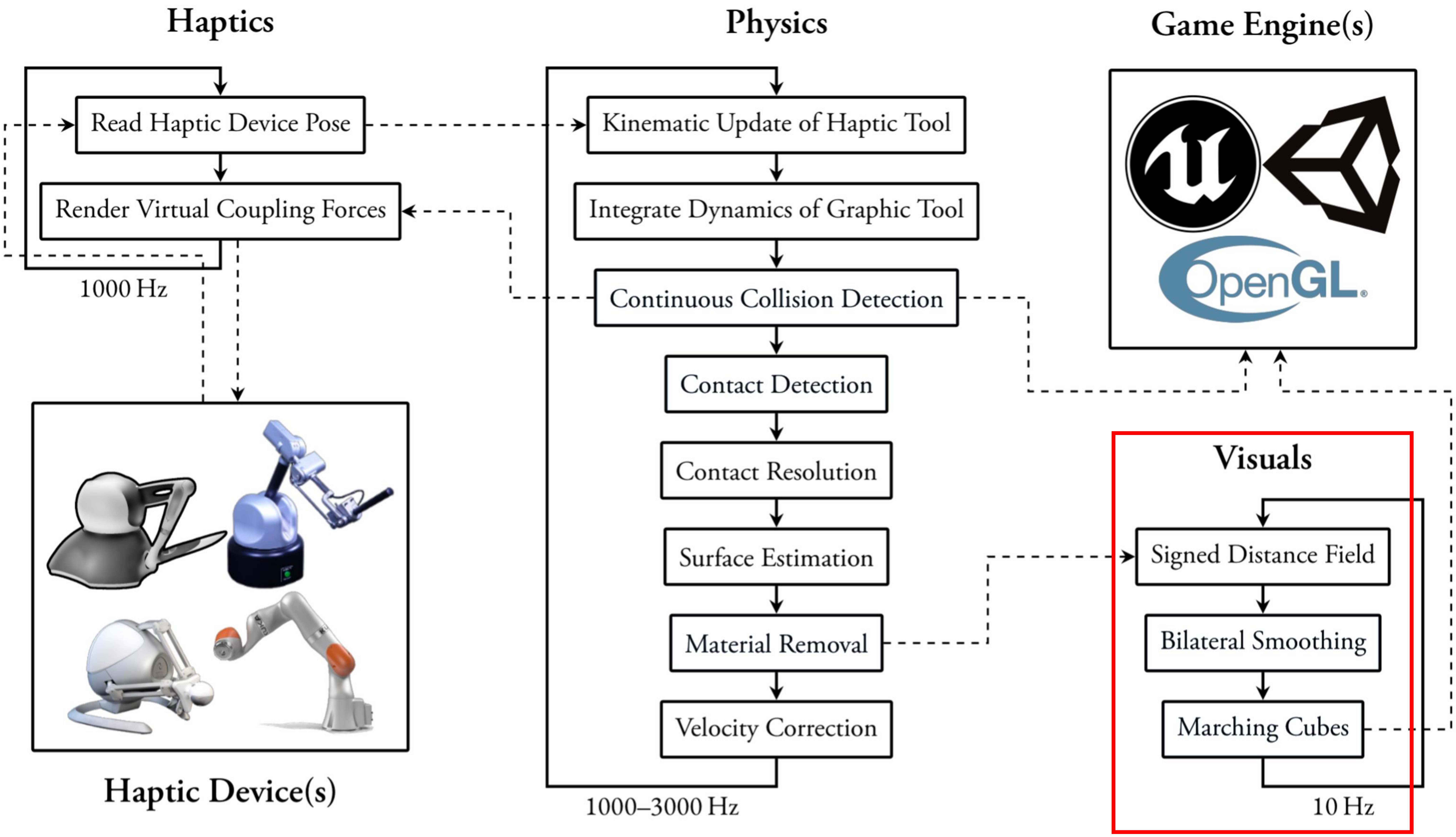




Tool Sounds

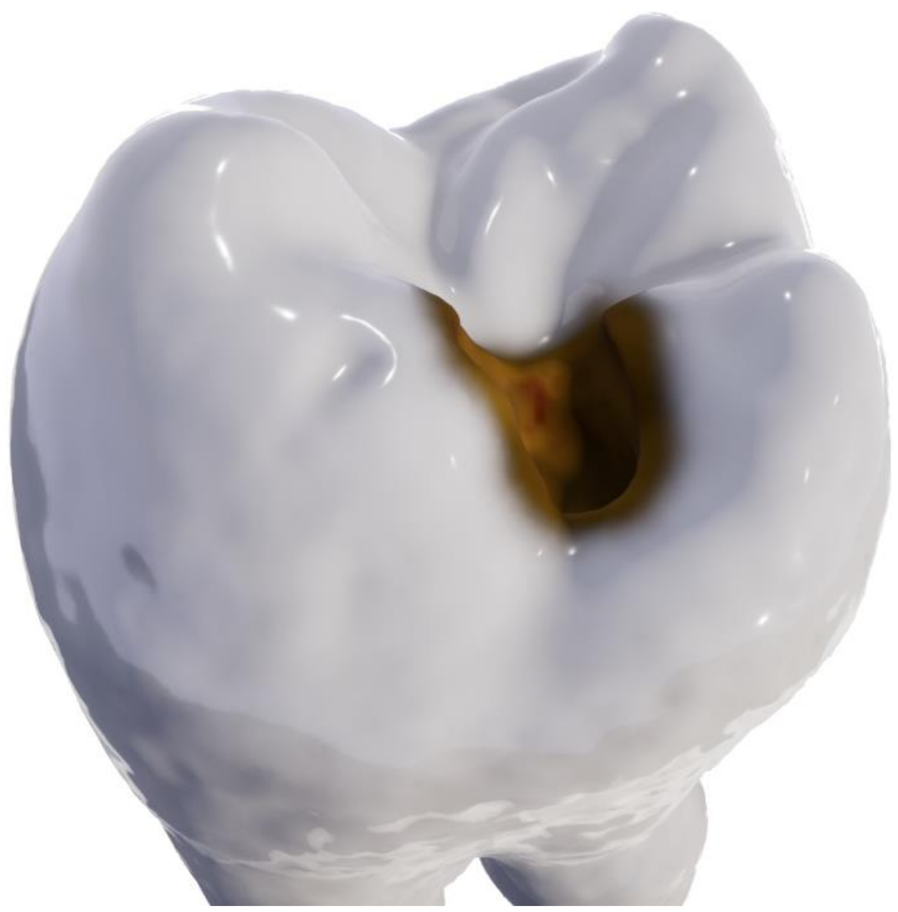


Simulation: Visualization



Visualization Pipeline

- Precomputed: mesh → spheres
- Maintain dynamic mesh at runtime
  - Spheres → mesh (reverse)
- Interactive rates
- Visual quality & color



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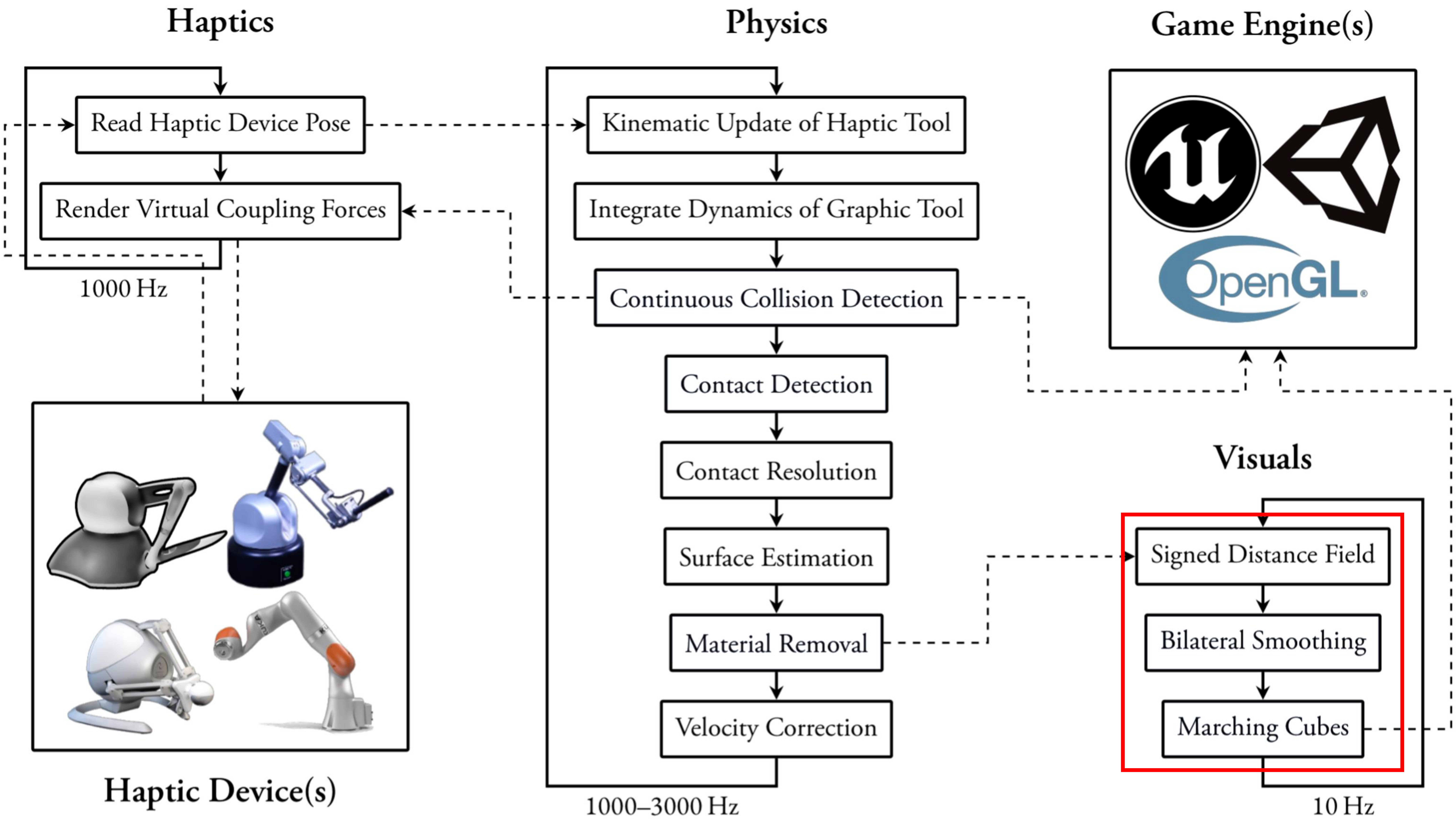
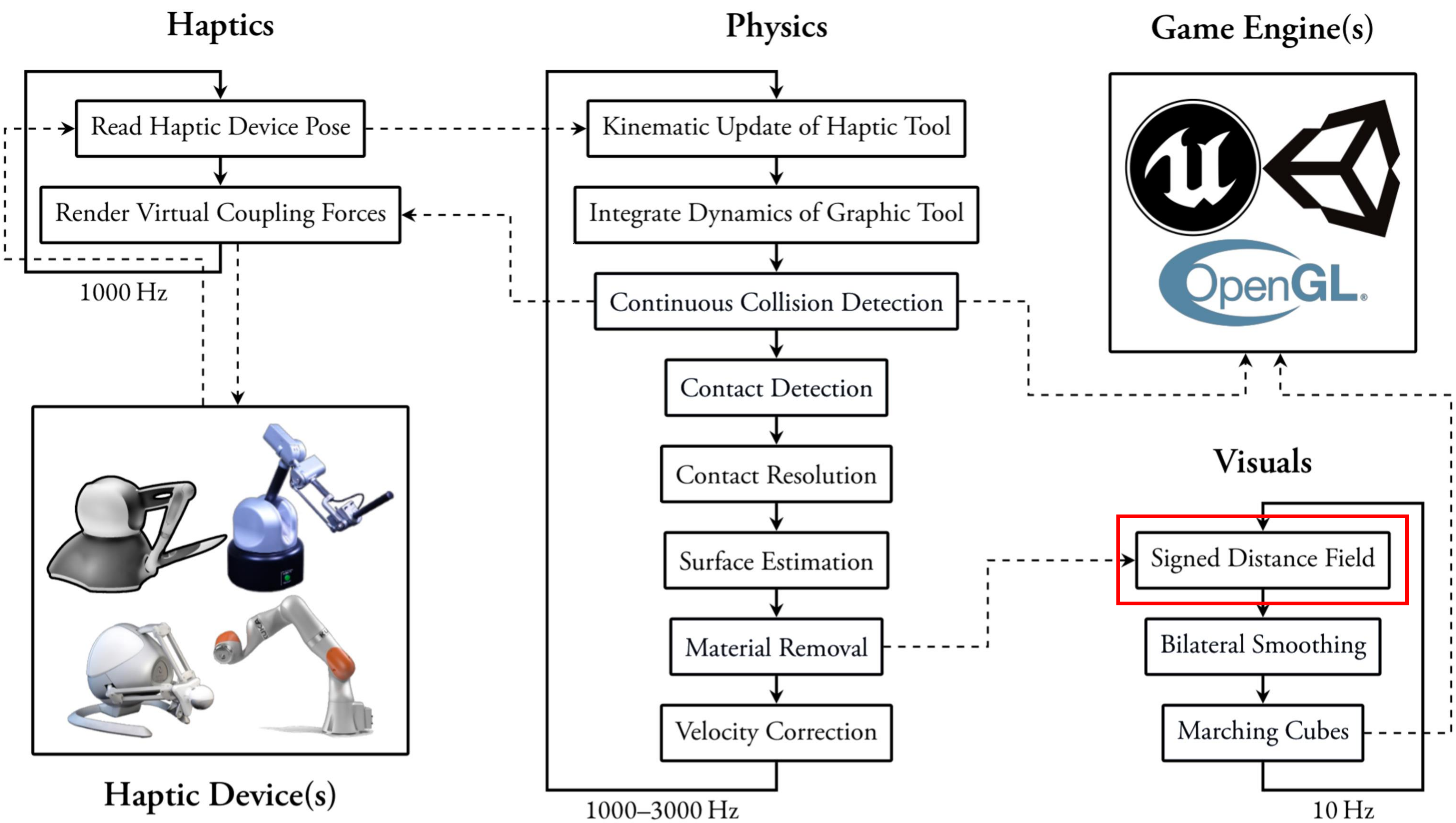
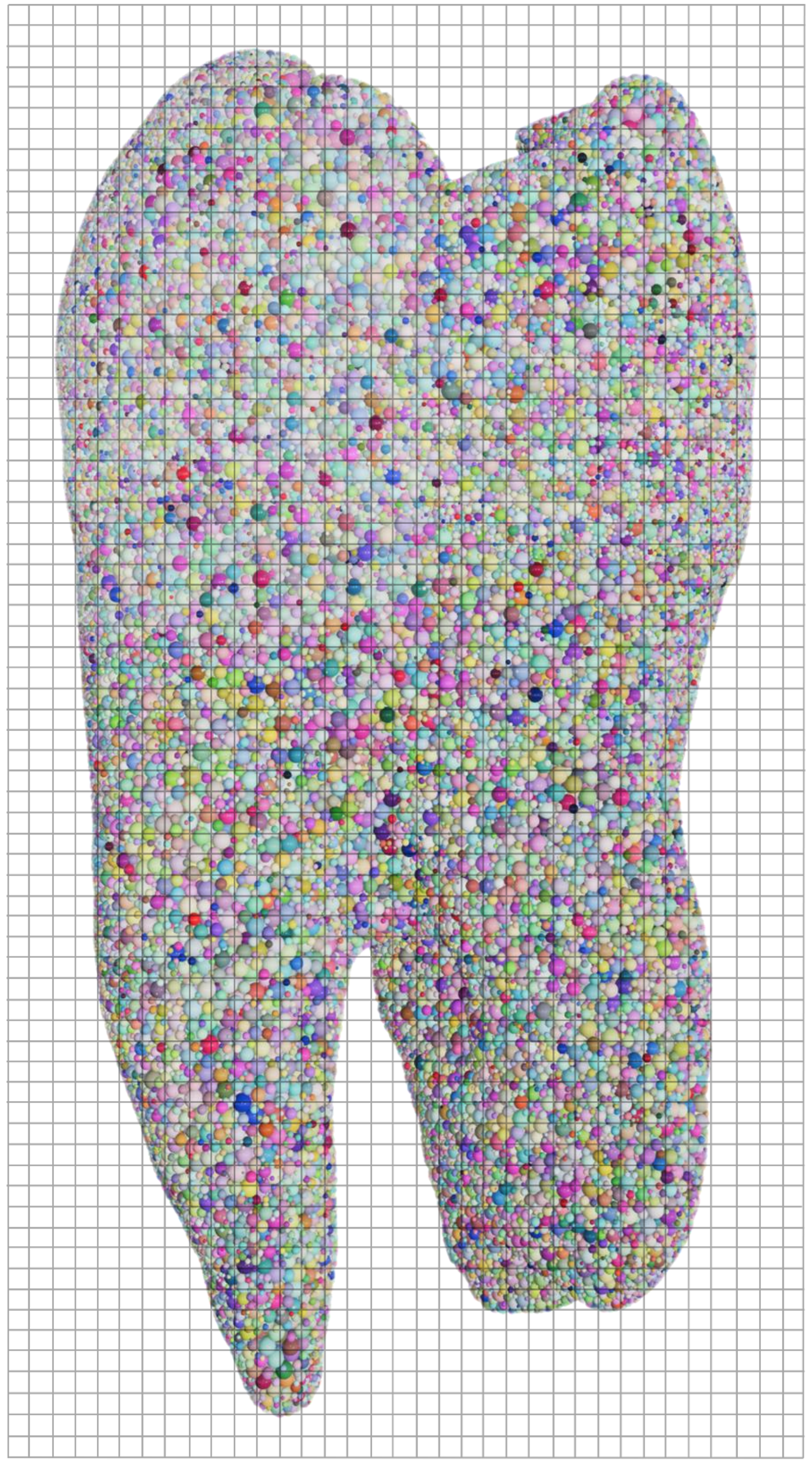


Visualization Pipeline



Visualization (Signed Distance Field)



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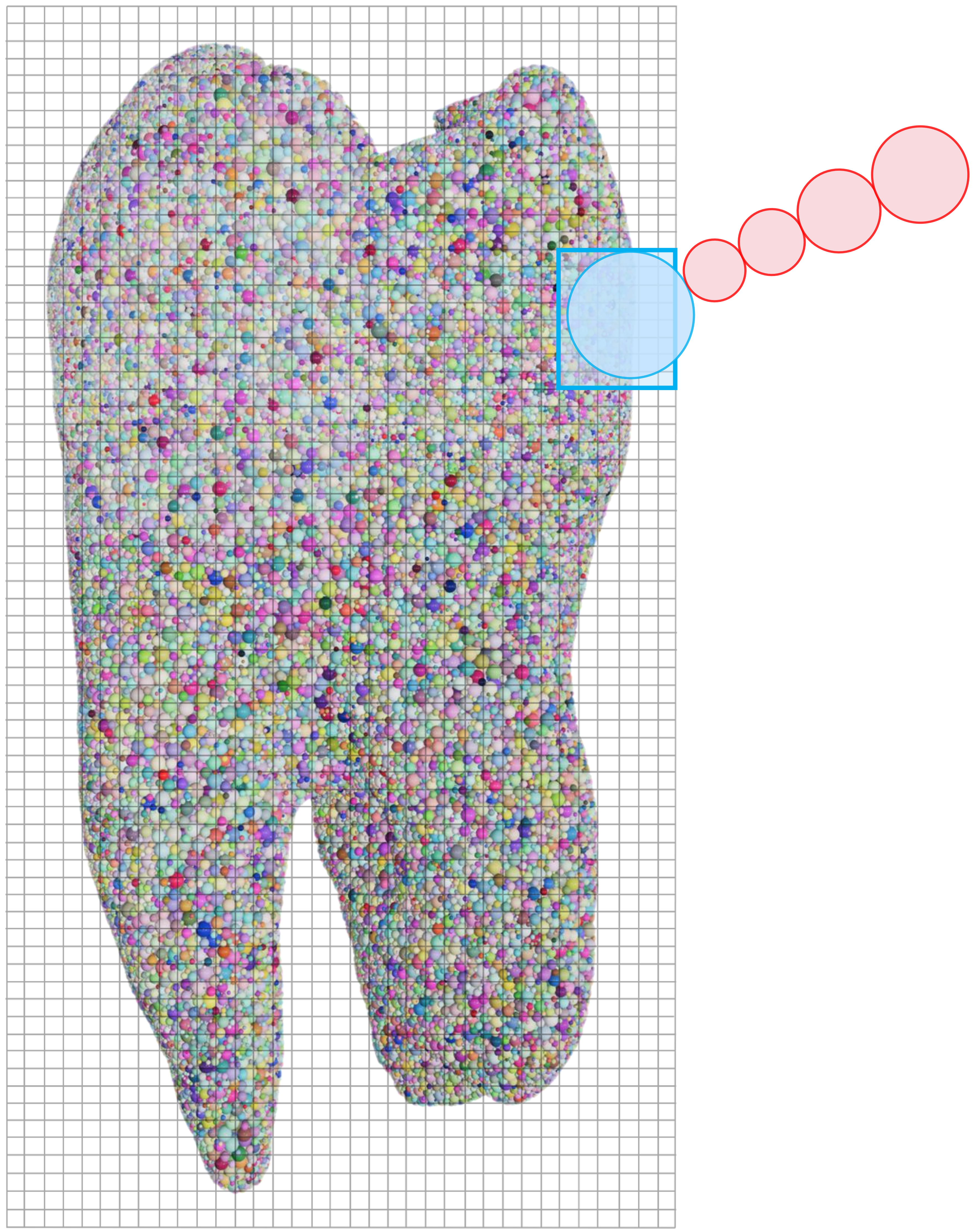

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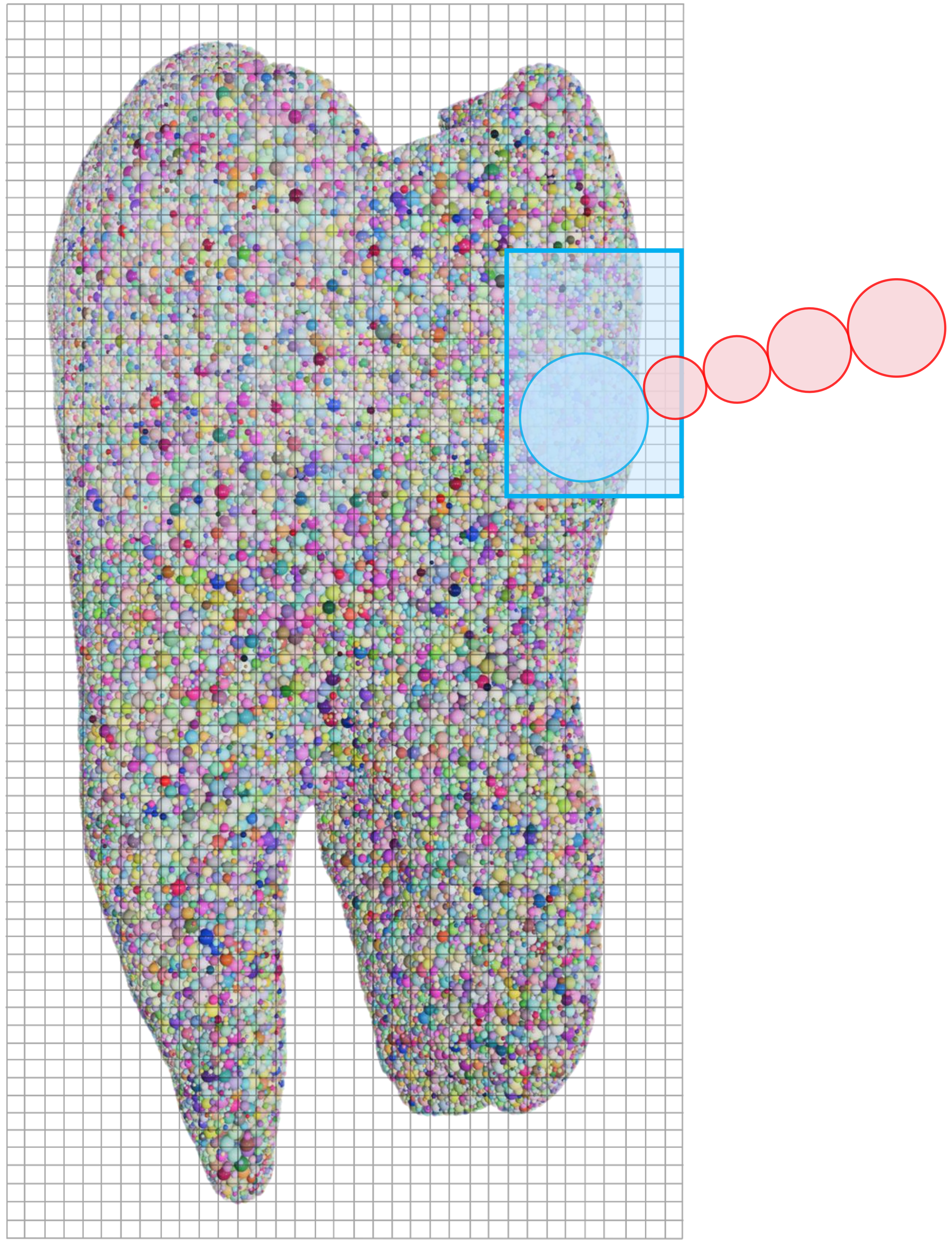

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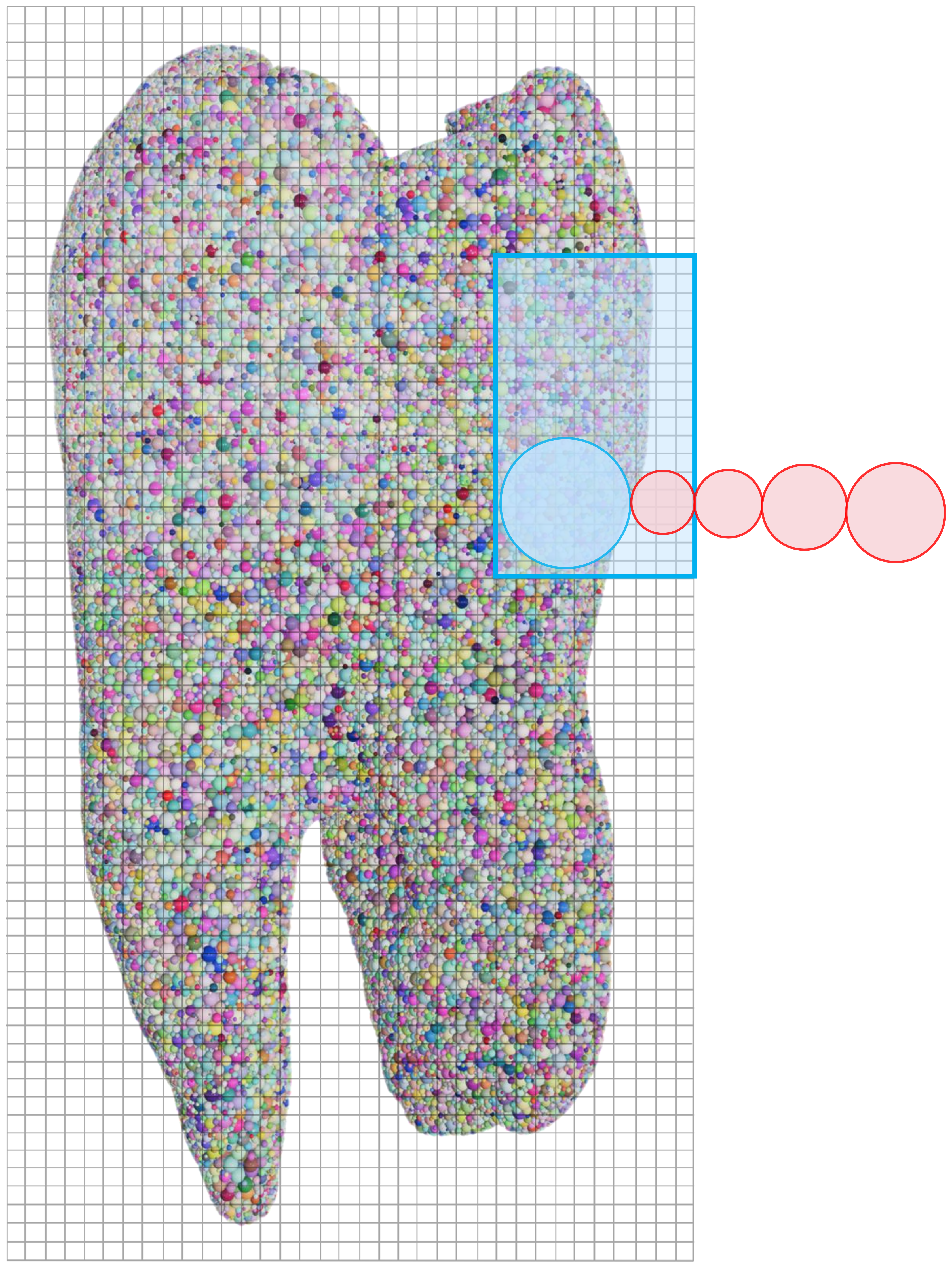

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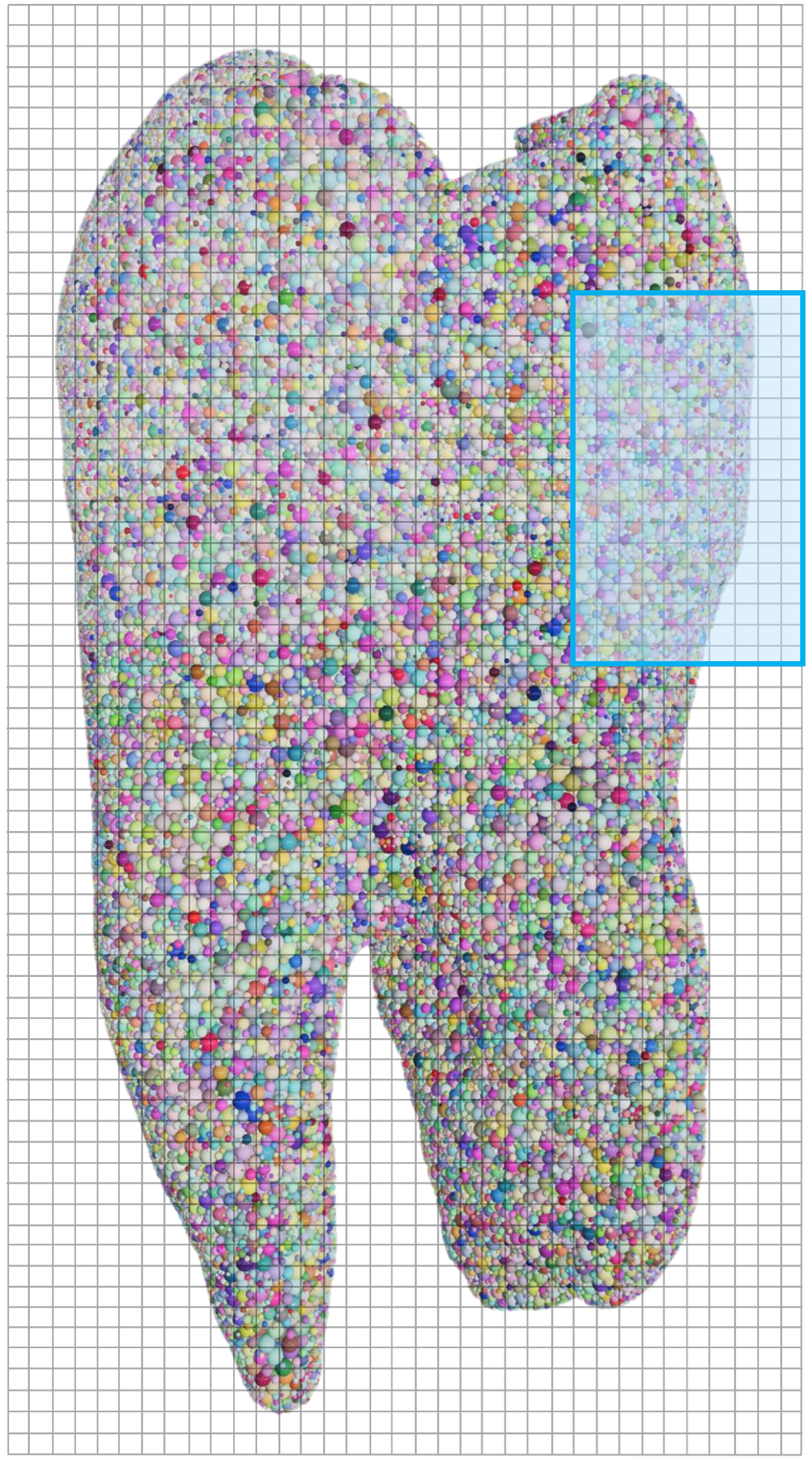
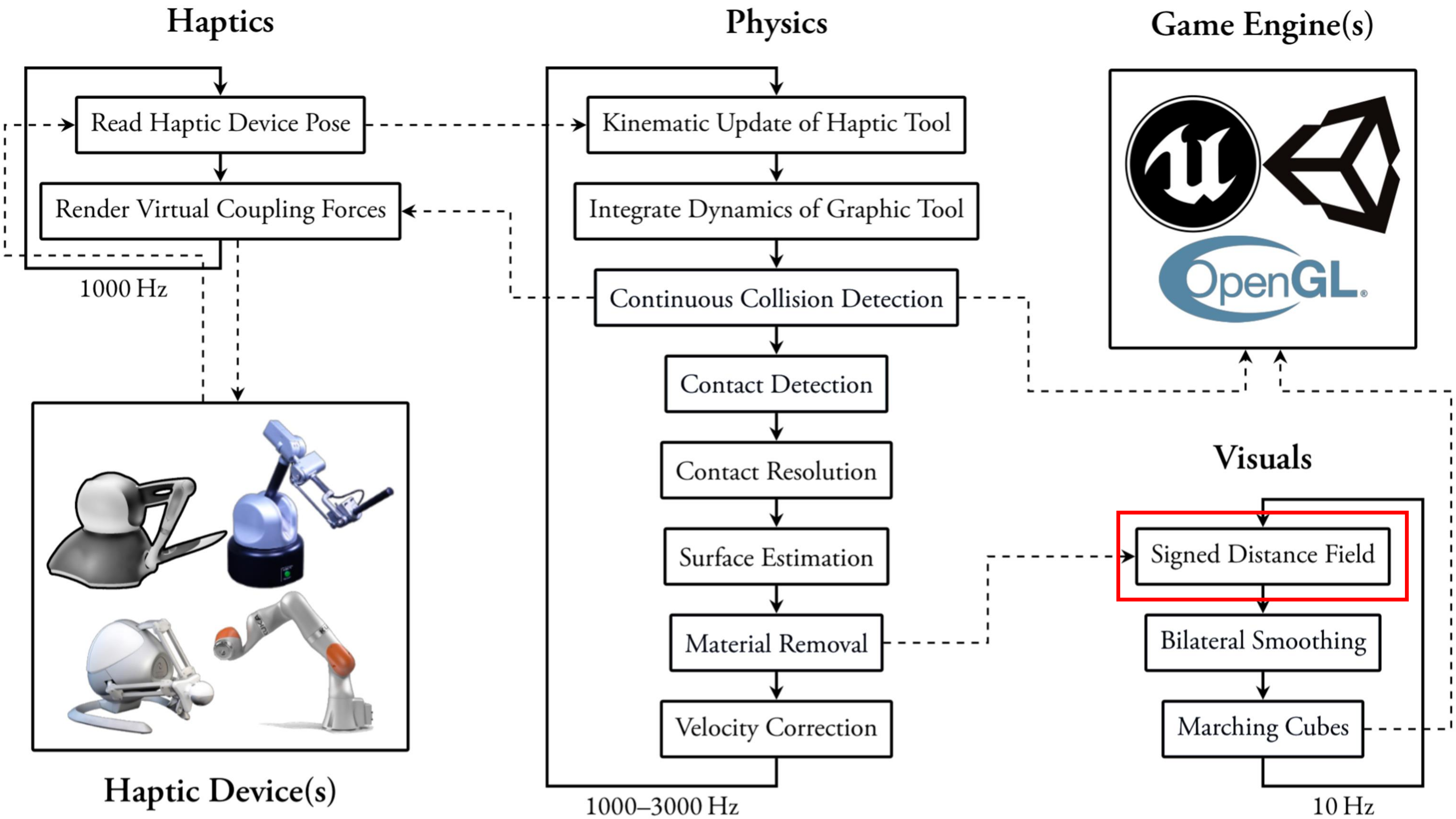
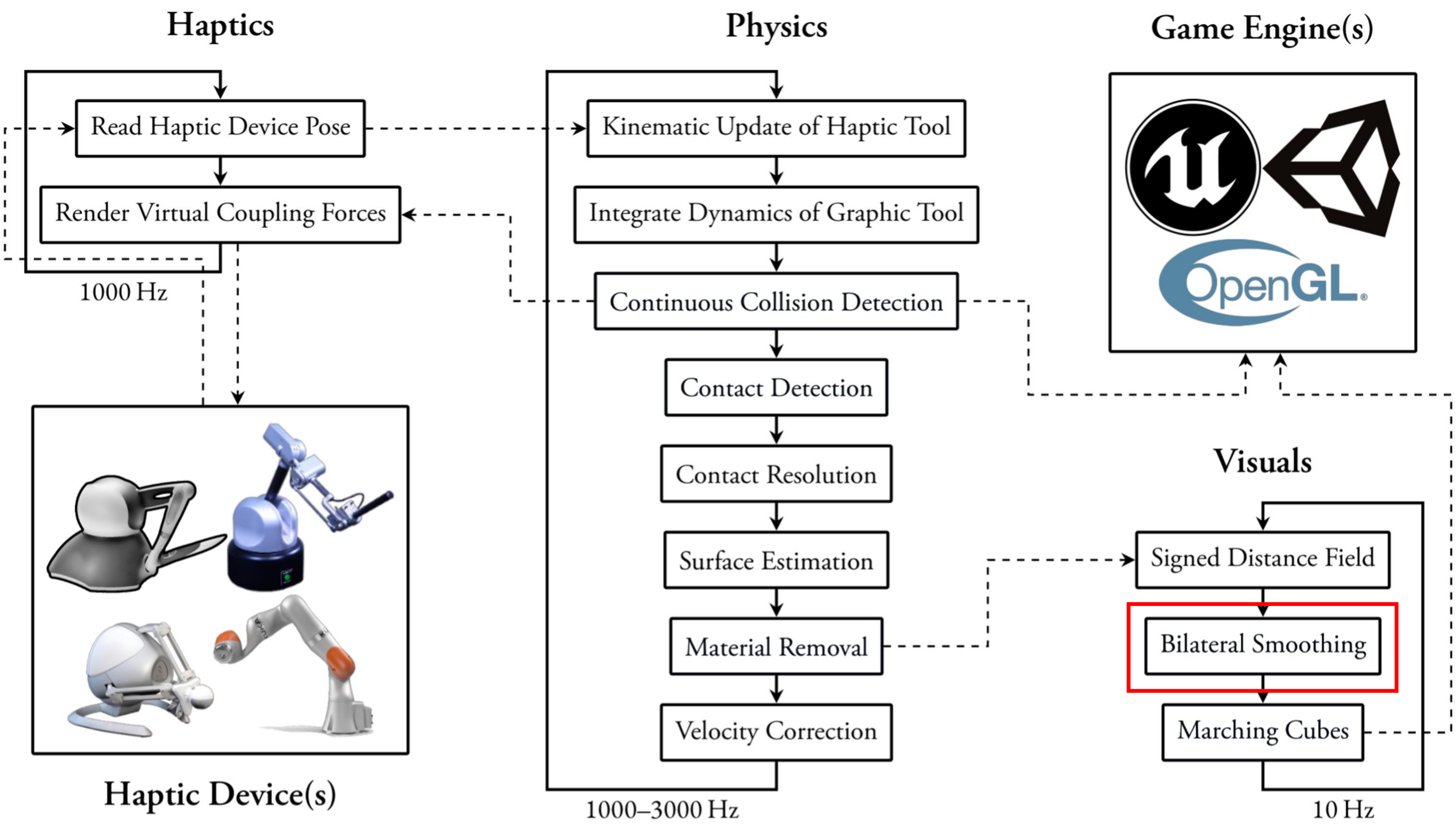


Simulation: Signed Distance Field



Simulation: Bilateral Smoothing



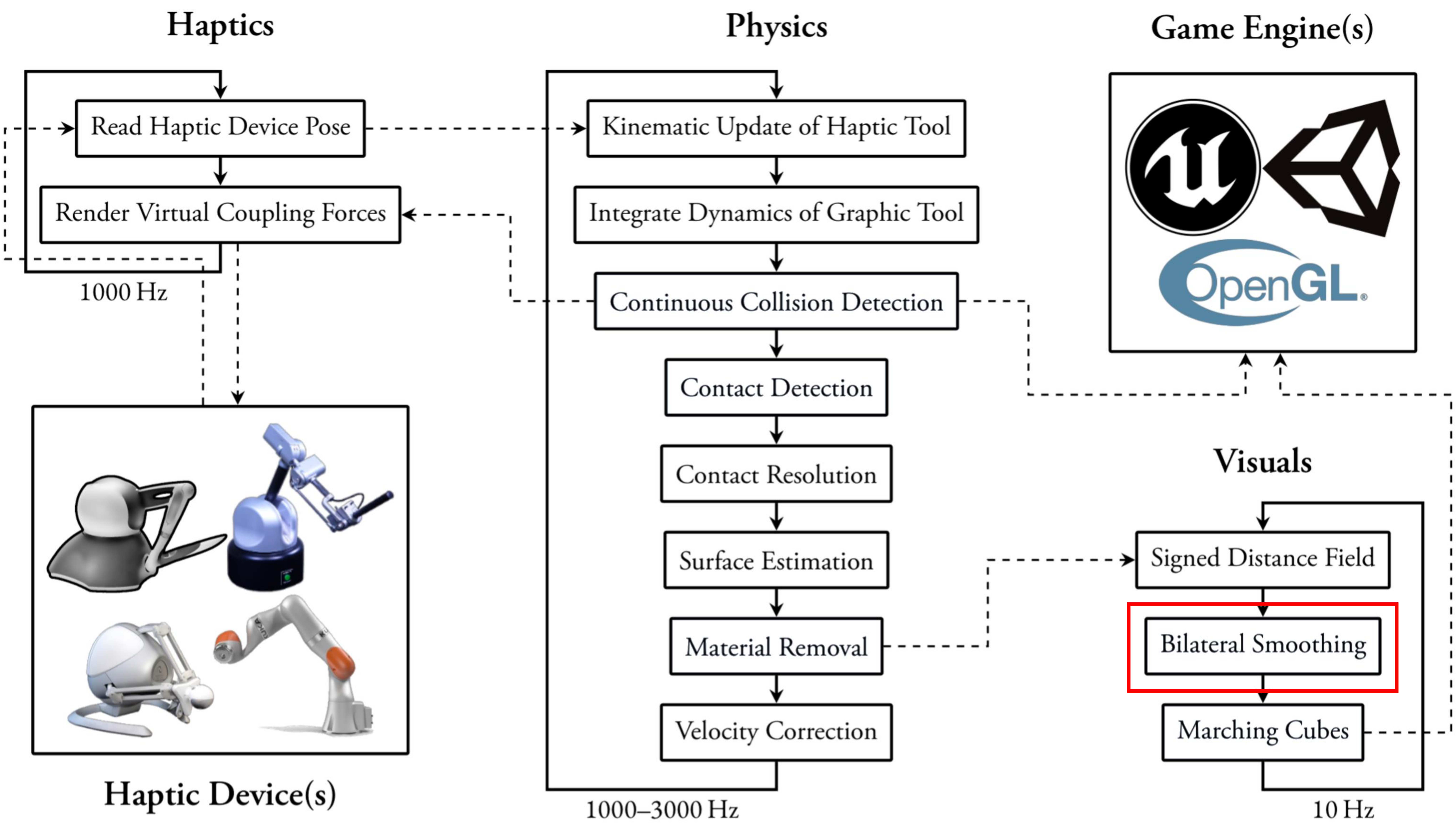
Visualization (Bilateral Smoothing)

No smoothing,
Triangle normals

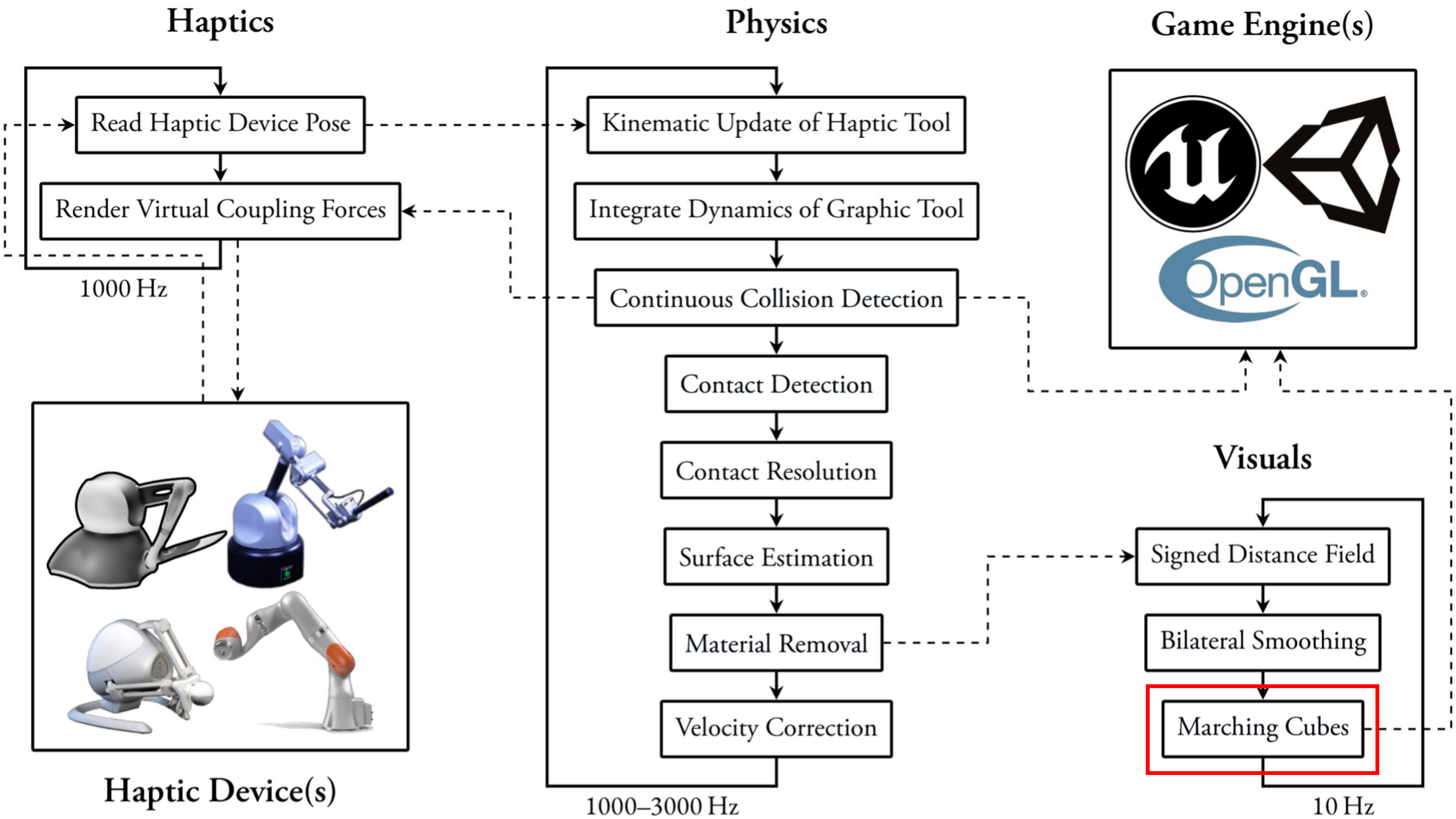
Smoothing,
Triangle normals

Smoothing,
Sphere normals

Simulation: Bilateral Smoothing

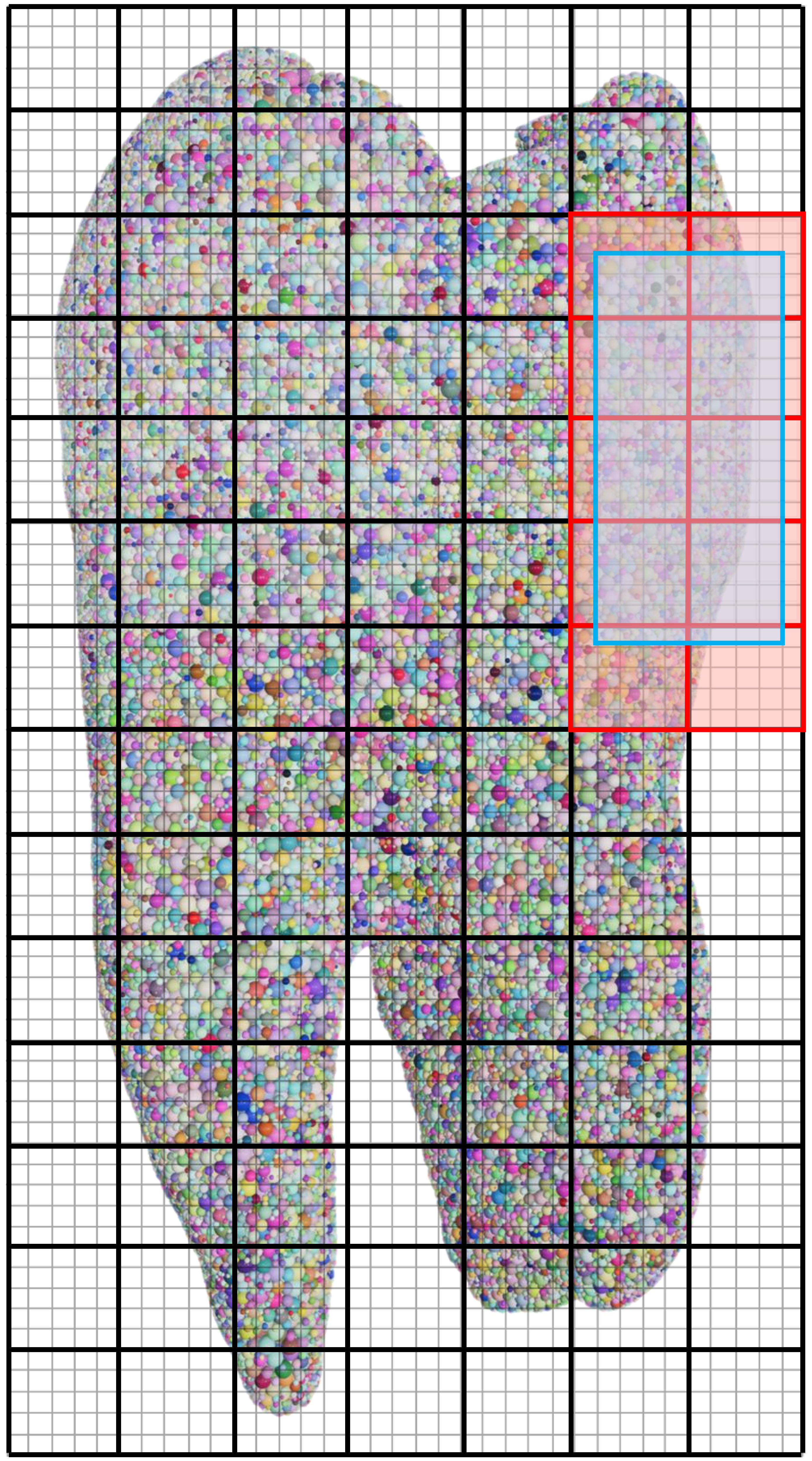


Simulation: Marching Cubes



Visualization (Marching Cubes)

- Parallel MC on GPU
  - Extended by LERP'd sphere normal & colors
- Coarser grid to store triangles
- Reduce data by vertex pooling
  - Including normal & colors



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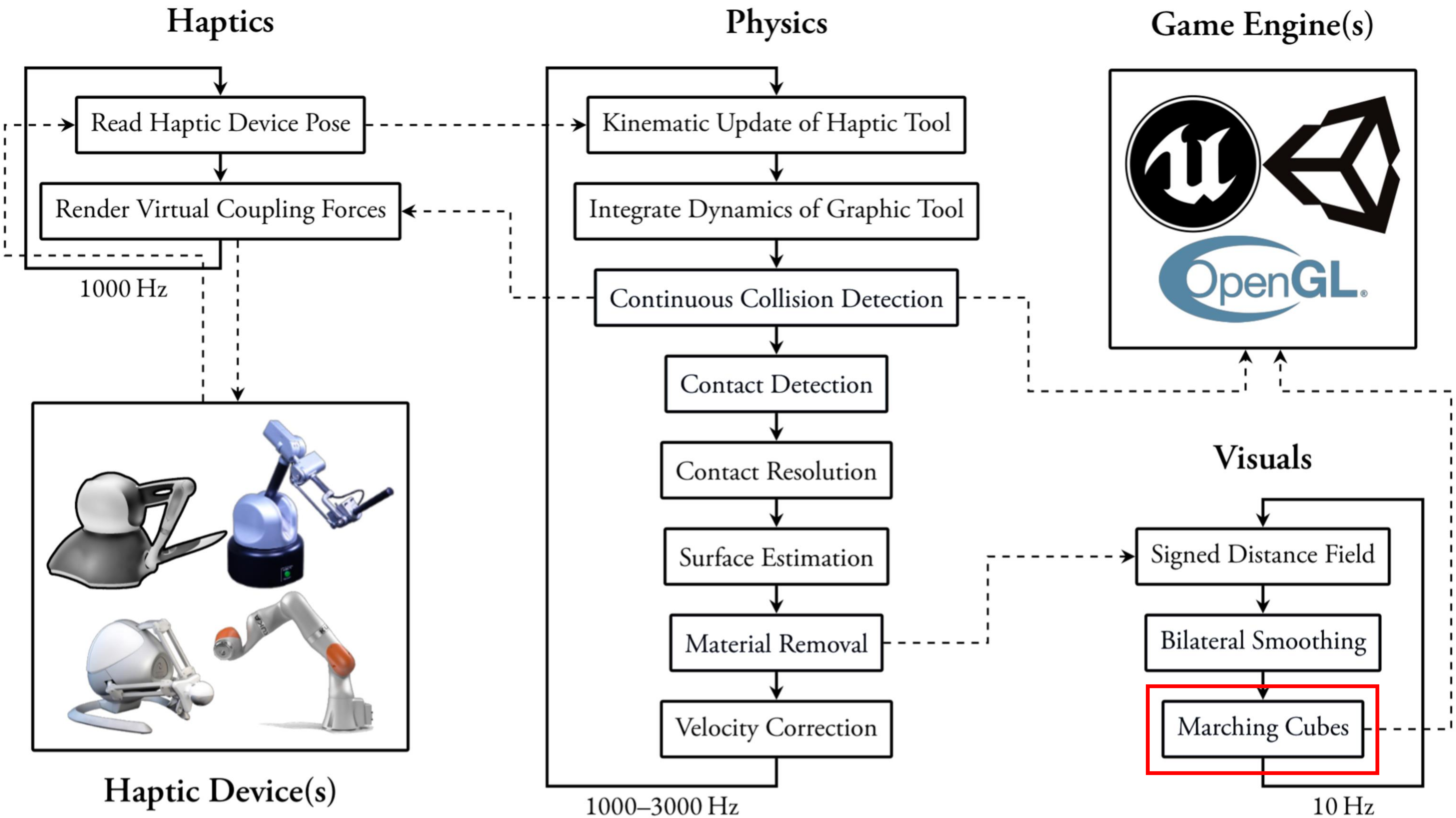
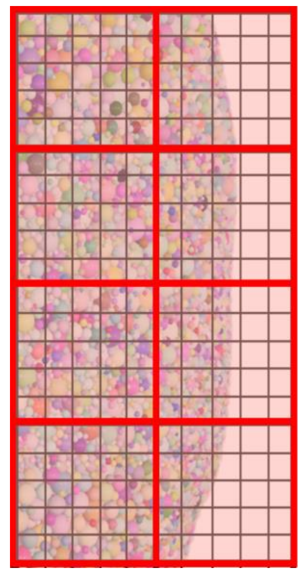
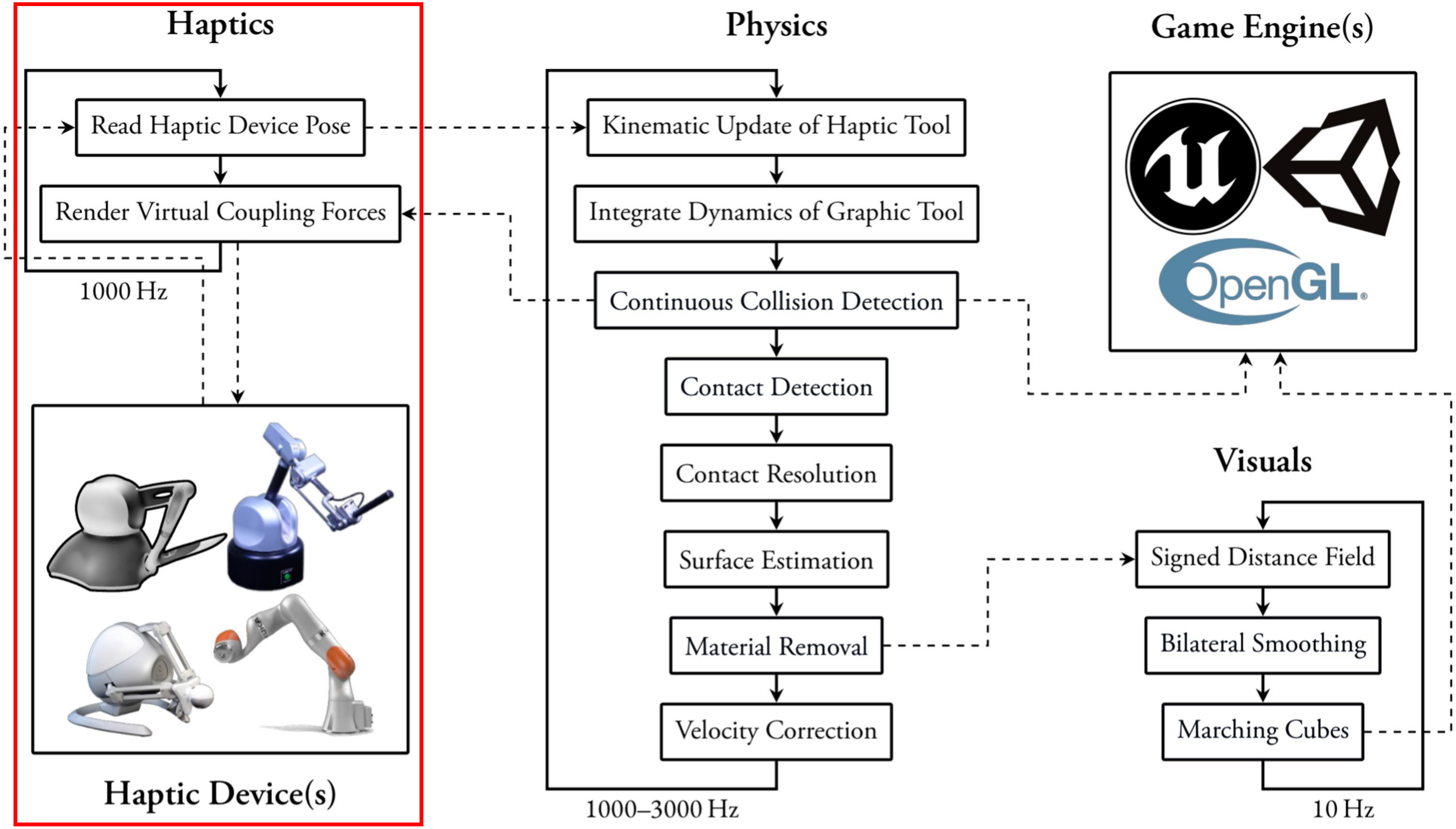




Simulation: Haptics

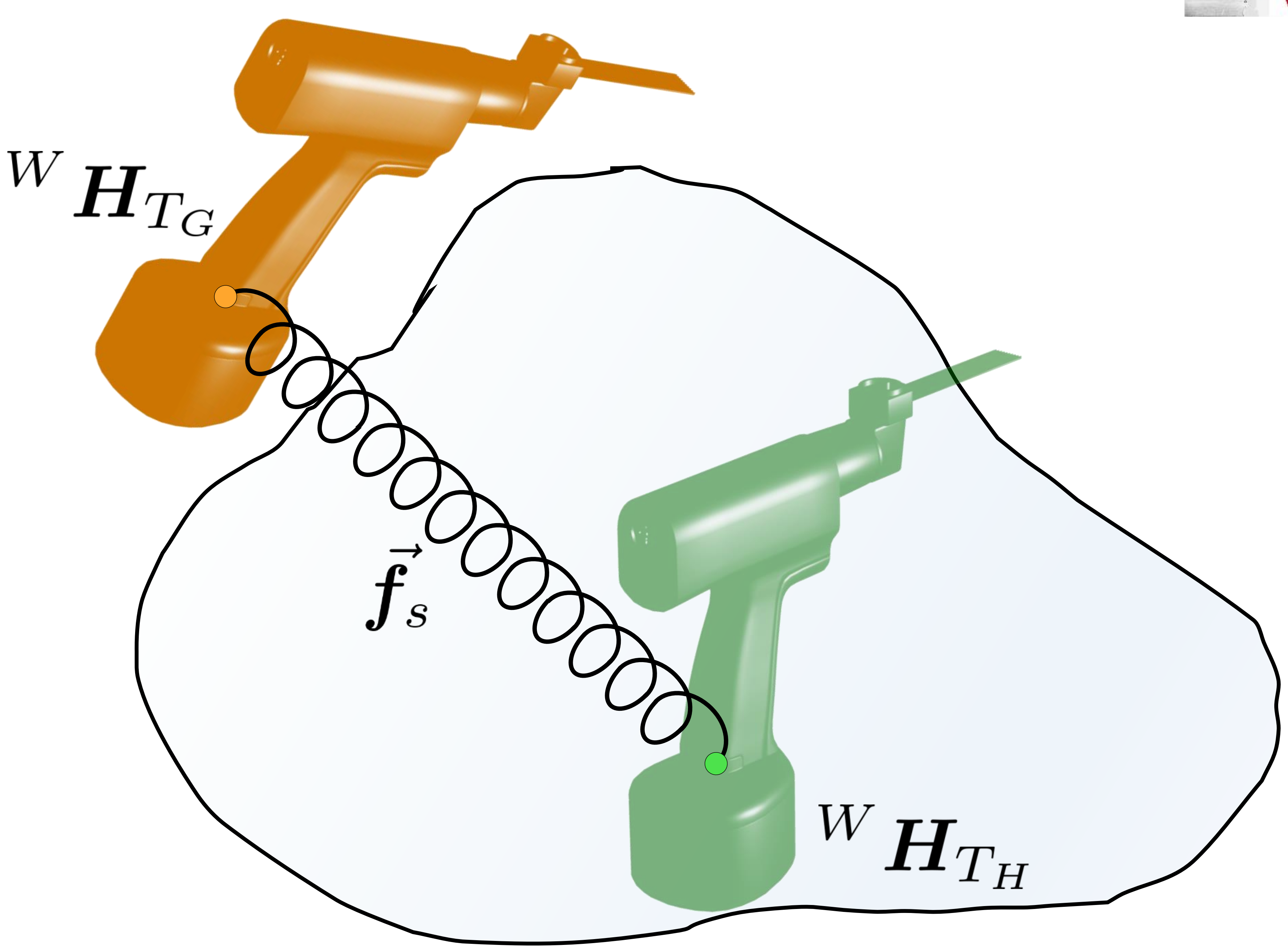


Haptics

- Two instances of the same tool (T_H, T_G)
- Interaction spring between real and virtual
  - Based on virtual coupling

$$\vec{\boldsymbol{f}}_s = [\boldsymbol{p}(T_G) - \boldsymbol{p}(T_H)]\, k_t - [\vec{\boldsymbol{v}}(T_G) - \vec{\boldsymbol{v}}(T_H)]\, b_t$$

$$\vec{\boldsymbol{\tau}}_s = \boldsymbol{R}\left({}^W\boldsymbol{H}_{T_G}\, {}^W\boldsymbol{H}_{T_H}^{-1}\right) k_r - [\vec{\boldsymbol{\omega}}(T_G) - \vec{\boldsymbol{\omega}}(T_H)]\, b_r$$



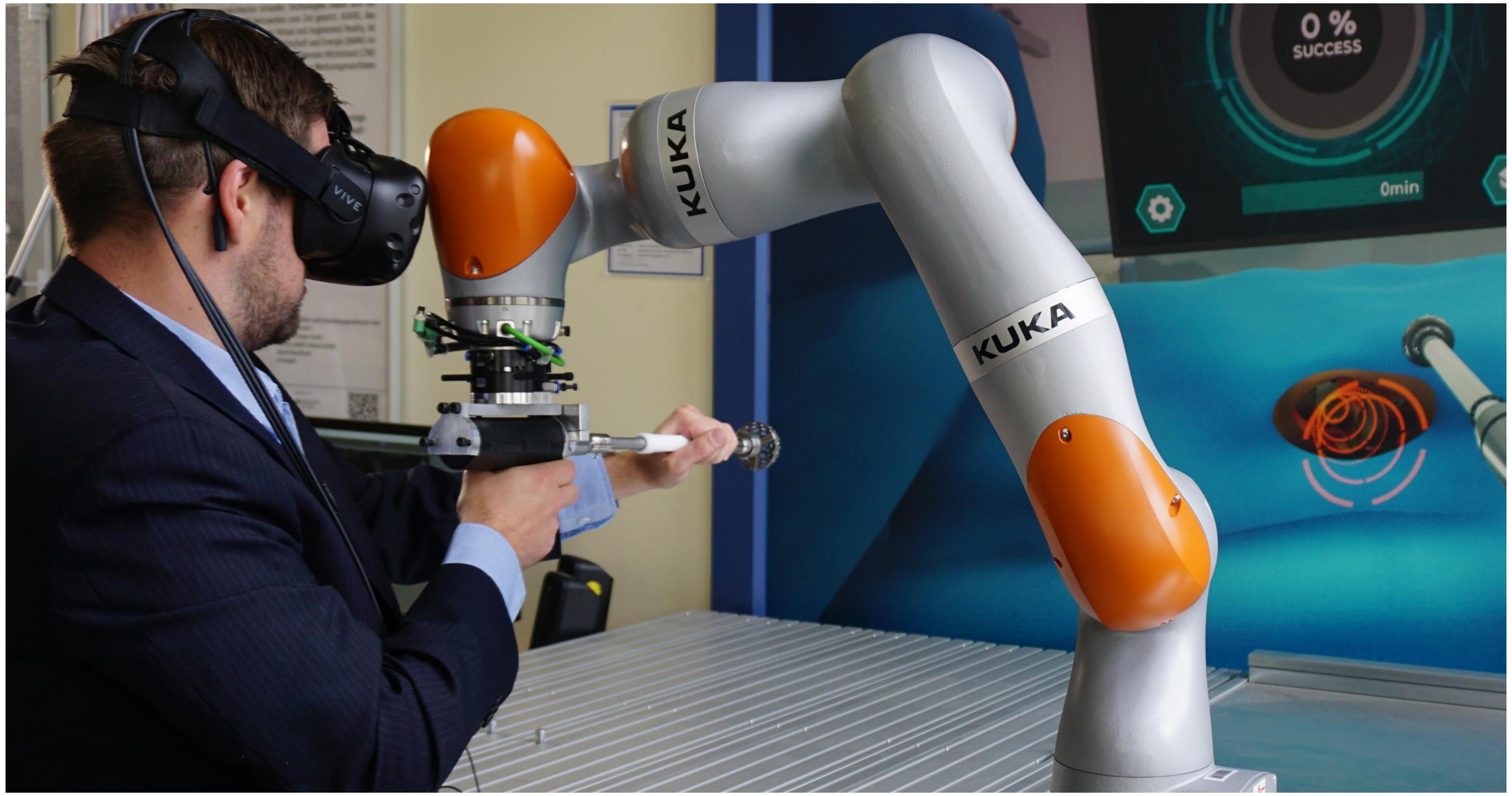
Improving Haptic Stability

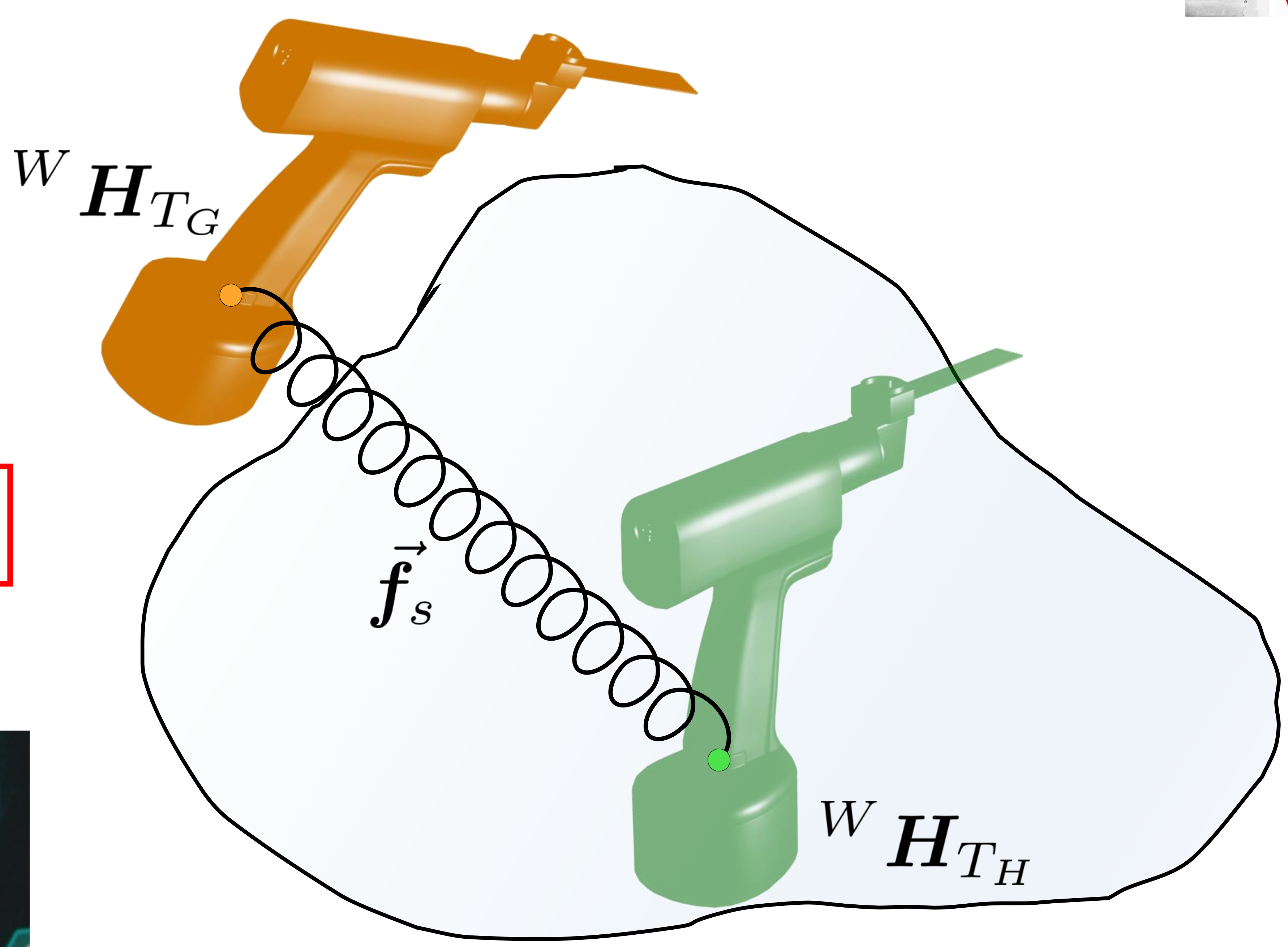
- Additional damping terms

$$\vec{\boldsymbol{f}}_s = [\boldsymbol{p}(T_G) - \boldsymbol{p}(T_H)]\,k_t - [\vec{\boldsymbol{v}}(T_G) - \vec{\boldsymbol{v}}(T_H)]\,b_t \boxed{- \vec{\boldsymbol{v}}(T_H) b_t^{abs}}$$

$$\vec{\boldsymbol{\tau}}_s = \boldsymbol{R}\left({}^W\boldsymbol{H}_{T_G}\,{}^W\boldsymbol{H}_{T_H}^{-1}\right) k_r - [\vec{\boldsymbol{\omega}}(T_G) - \vec{\boldsymbol{\omega}}(T_H)]\,b_r \boxed{- \vec{\boldsymbol{\omega}}(T_H) b_r^{abs}}$$

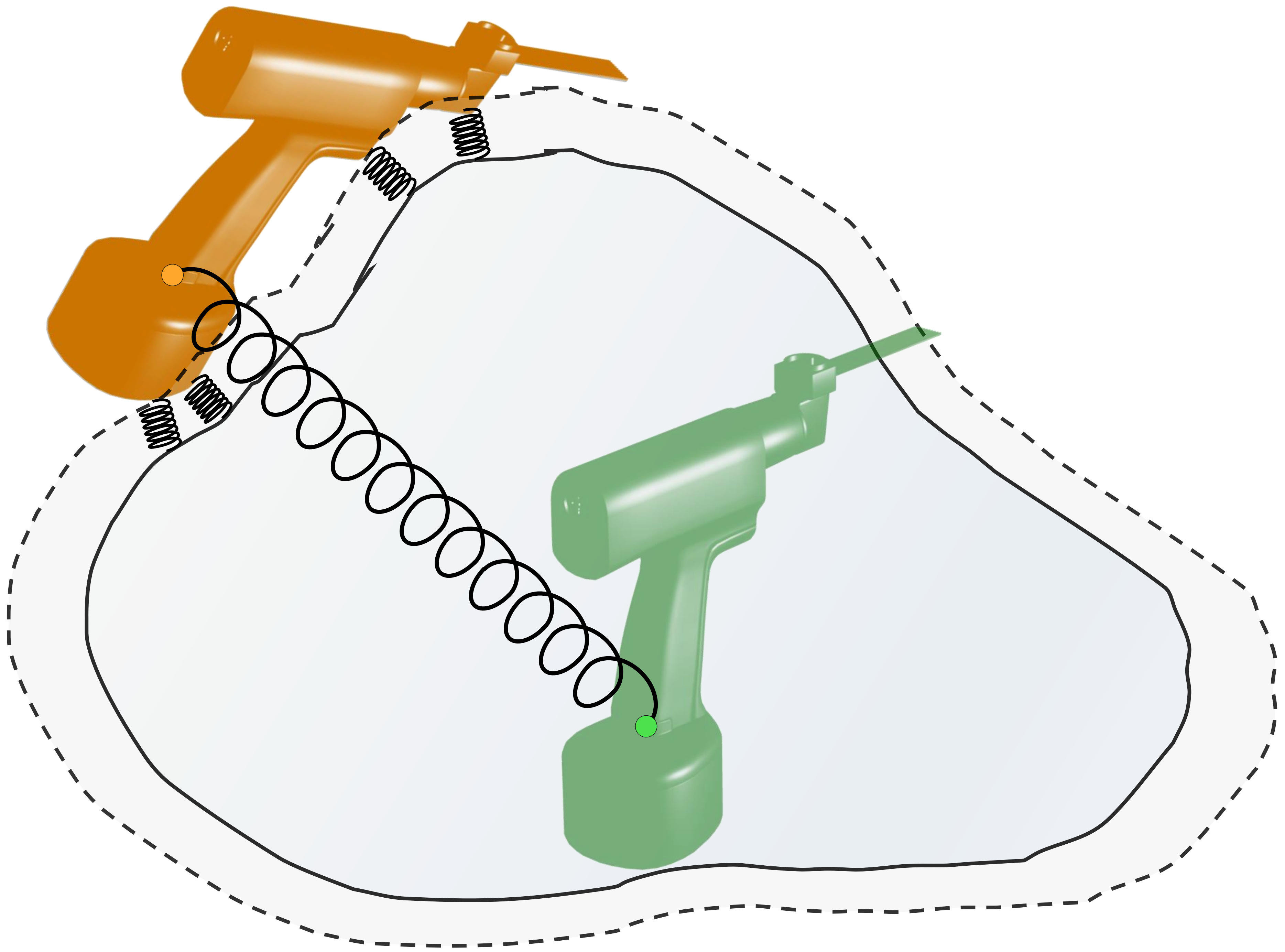
$$\vec{\boldsymbol{\tau}}_s' = \vec{\boldsymbol{\tau}}_s \boxed{- [(\boldsymbol{c} - \boldsymbol{p}_c) \times \dot{\boldsymbol{c}}]\, b_r^{ext}}$$





Improving Haptic Stability

- Force saturation: contacts and interaction
- High stiffnesses ⇒ low felt inertia
- Low accelerations ⇒ high sim. stability



Improving Haptic Stability

- Force saturation: contacts and interaction
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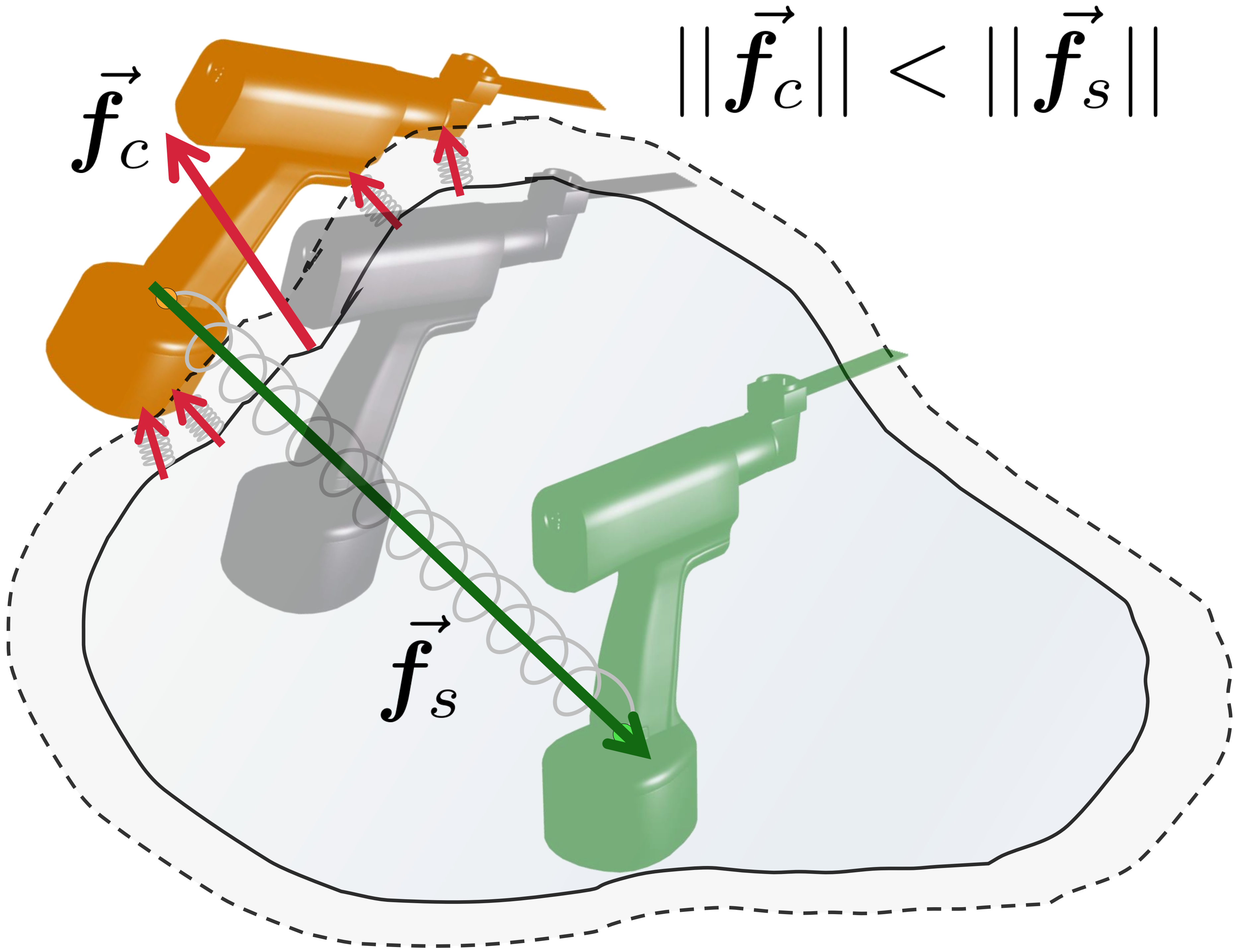
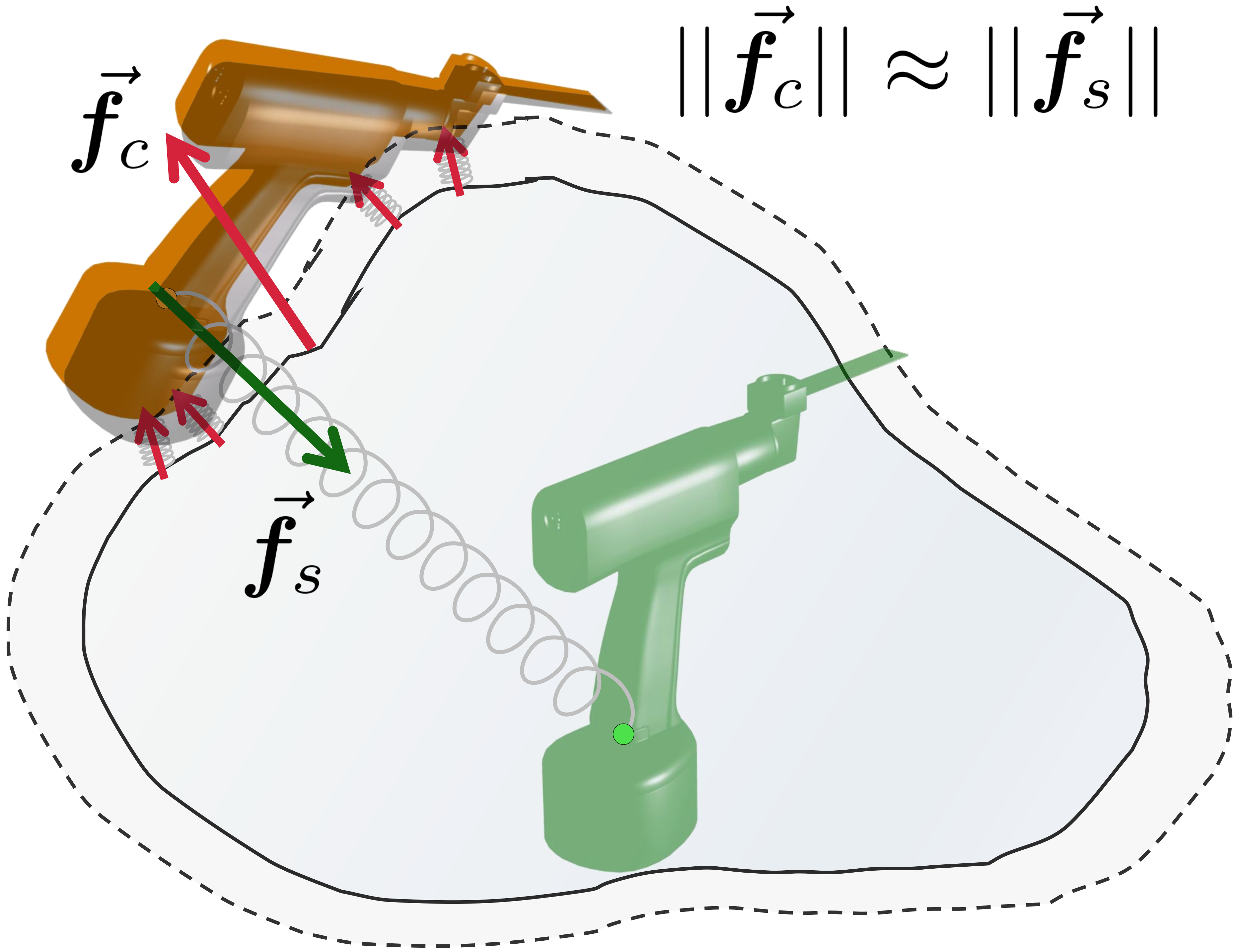


Improving Haptic Stability

- Force saturation: contacts and interaction
- High stiffnesses ⇒ low felt inertia
- Low accelerations ⇒ high sim. stability
- Balance force magnitudes

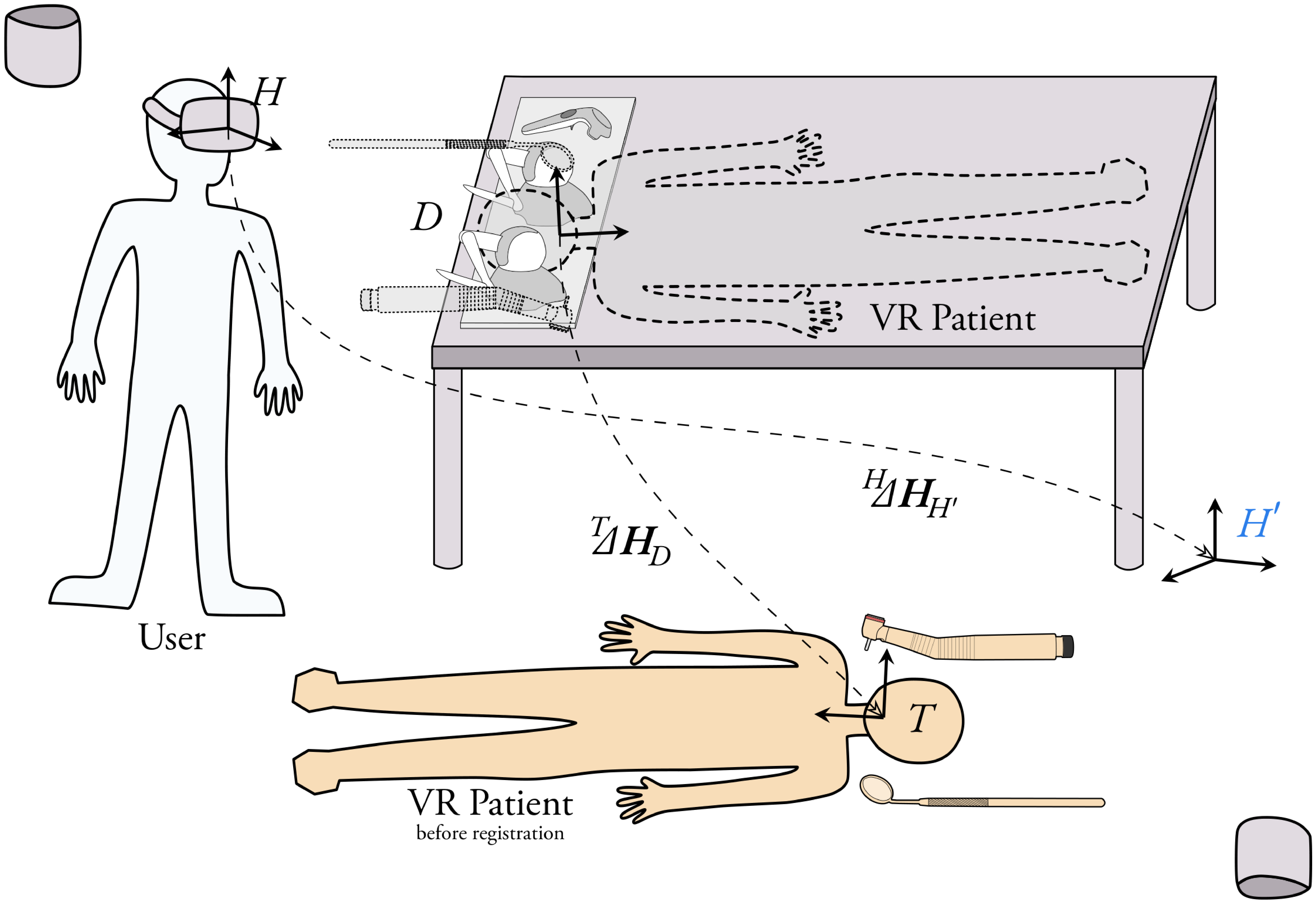


Haptics Demonstration

Haptic Registration in VR

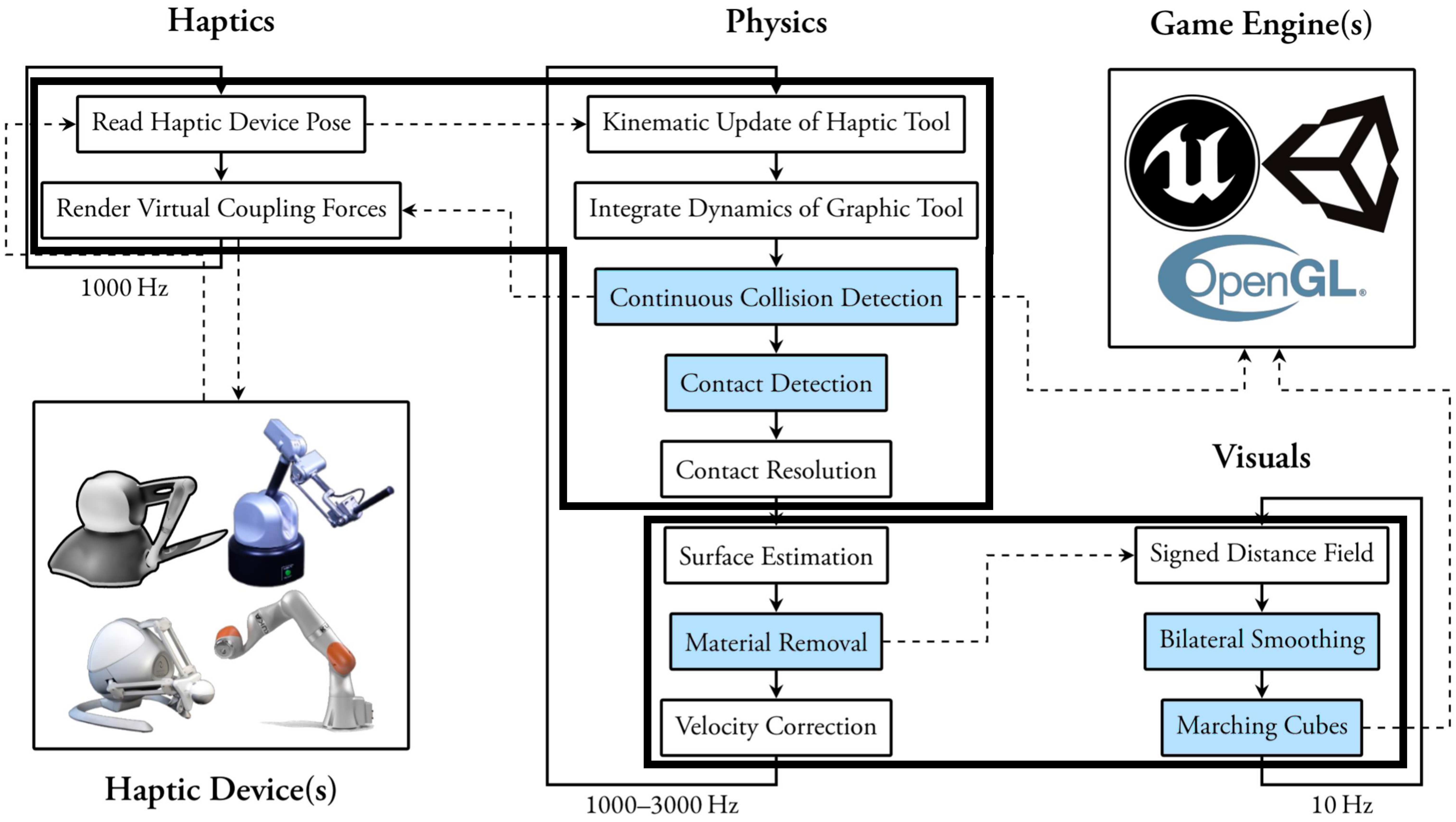
- Hand-tool alignment for skill transfer
- Use VR controller relative pose

Haptic Registration in VR



Simulation System

1. High-force haptic feedback ✓
2. Stepless haptic material removal ✓
3. Efficacy of HMD-based VR haptic simulators ◯



Applications

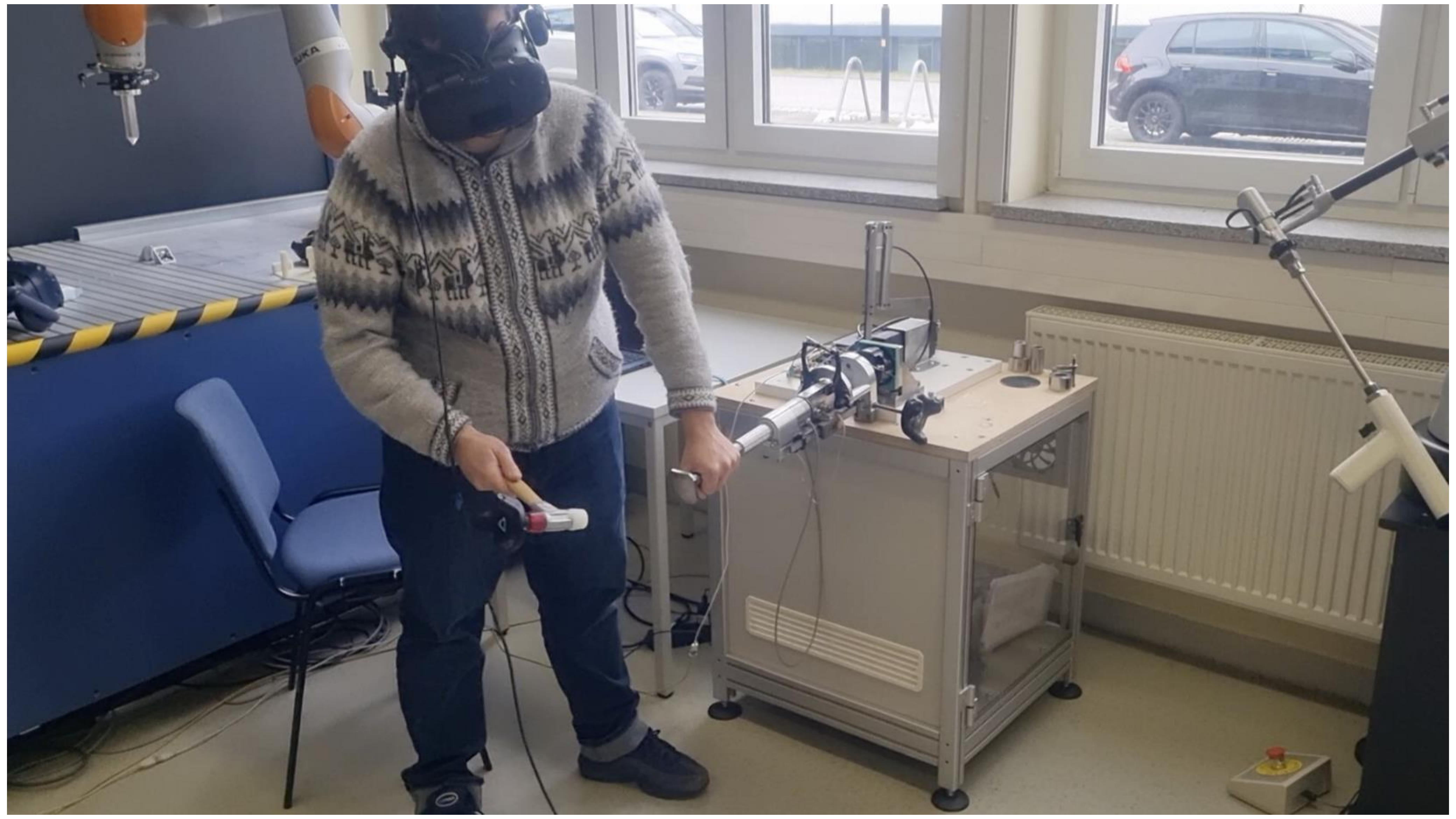
- Used my methods in 3 simulators

1. HIPS — Winner Best Tech DIVR AWARD 2019
2. DynamicHIPS — Winner Best Tech DIVR AWARD 2023
3. DentalSim

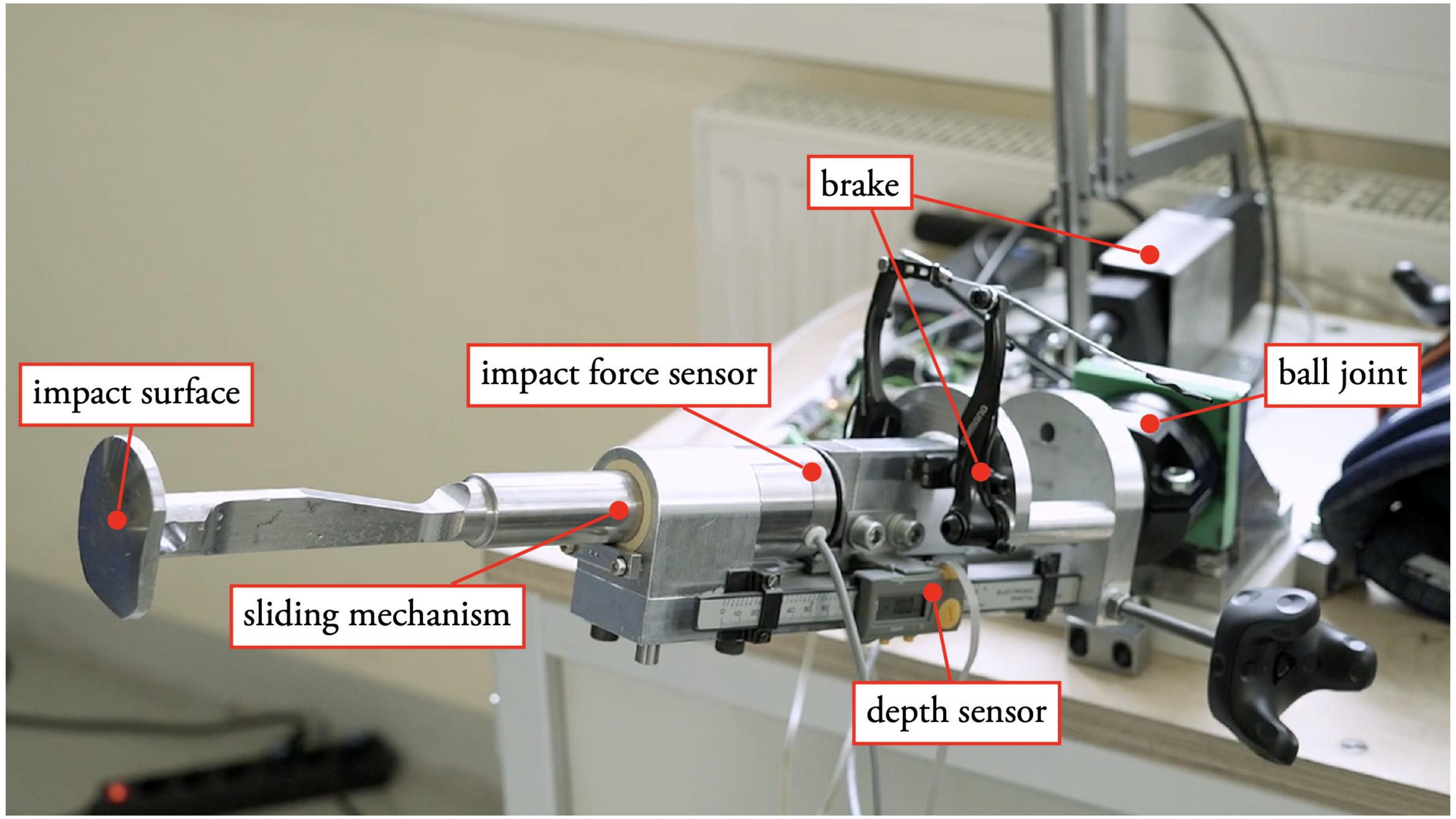
Hip Replacement Simulator

1. Kinesthetic haptic rendering for saw and reamer
   - Large forces during reaming

2. Hammering *impossible* to render on traditional hardware
   - New hardware with new rendering paradigm



Haptic Rendering of Hammering

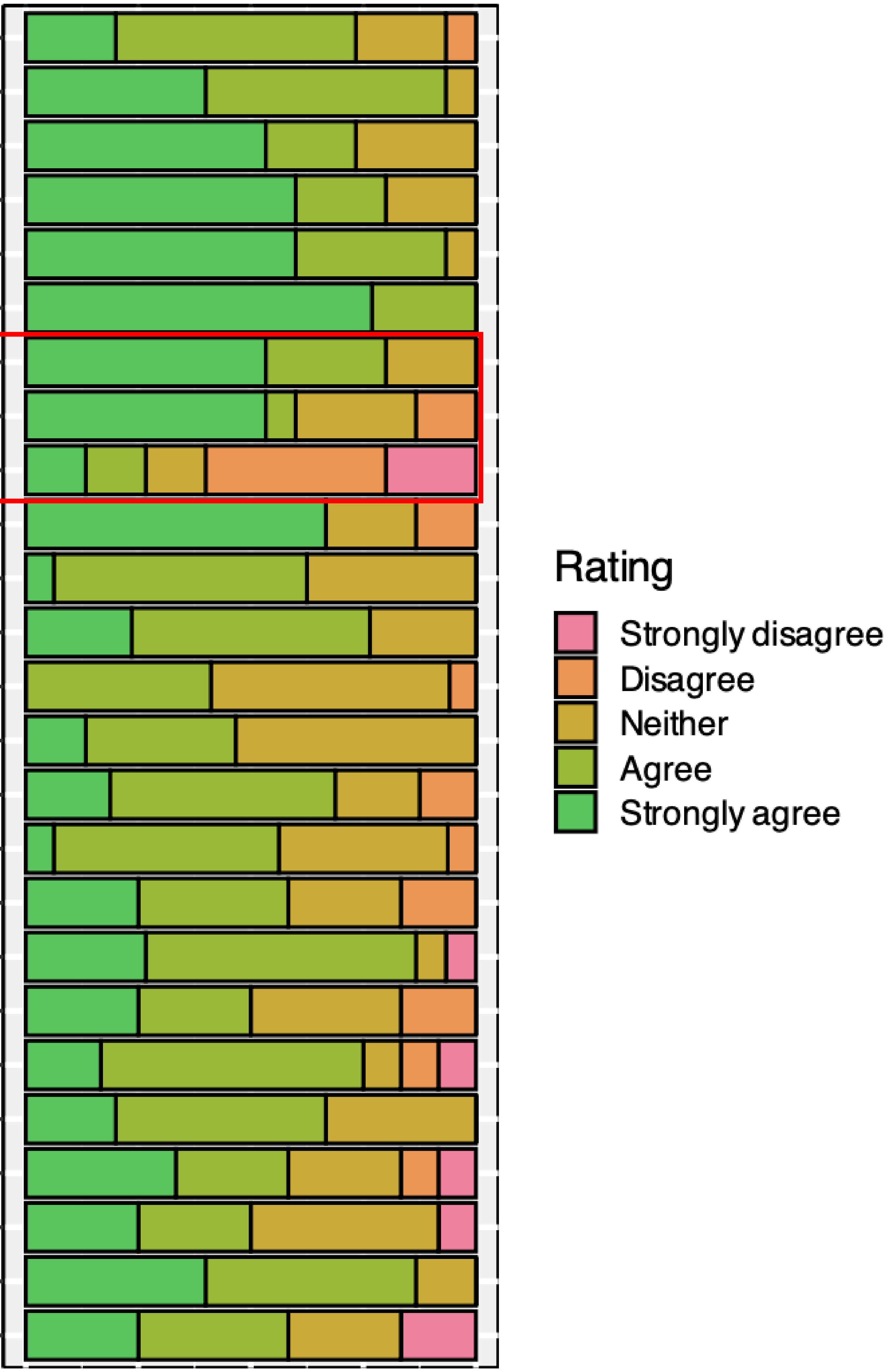


Haptic Rendering of Hammering

HIPS Expert Feedback

HIPS Expert Feedback

The 3D visualization of the situs was realistic.	G01
The 3D visualization of the OR was realistic.	G02
The HIPS simulator helps in learning the implantation of a hip prosthesis.	G03
Time was going by fast while I was using the HIPS simulator.	G04
Getting accommodated to using the HIPS simulator was easy.	G05
Using the HIPS simulator gave me great pleasure.	G06
I would recommend the HIPS simulator to medical students (last year of study).	G07
I would recommend the HIPS simulator to residents (in training at hospital).	G08
I would recommend the HIPS simulator to attending surgeons (completed training).	G09
The HIPS simulator should support preparation of patient-specific operations.	G10
The sawing of the femur head was realistic.	M1_1
Regarding the visualization: the sawing of the femur head looked realistic.	M1_2
Regarding the haptics: the sawing of the femur head felt realistic.	M1_3
The reaming of the acetabulum was realistic.	M2_1
Regarding the visualization: the reaming of the acetabulum looked realistic.	M2_2
Regarding the haptics: the reaming of the acetabulum felt realistic.	M2_3
The hammering of the hip implant was realistic.	M3_1
Regarding the visualization: the hammer of the hip implant looked realistic.	M3_2
Regarding the haptics: the hammer of the hip implant felt realistic.	M3_3
The hammering of the femur rasp was realistic.	M4_1
Regarding the visualization: The hammer of the femur rasp looked realistic.	M4_2
Regarding the haptics: the hammer of the femur rasp felt realistic.	M4_3
The hammering of the femur implant was realistic.	M5_1
Regarding the visualization: the hammer of the femur implant looked realistic.	M5_2
Regarding the haptics: the hammer of the femur implant felt realistic.	M5_3

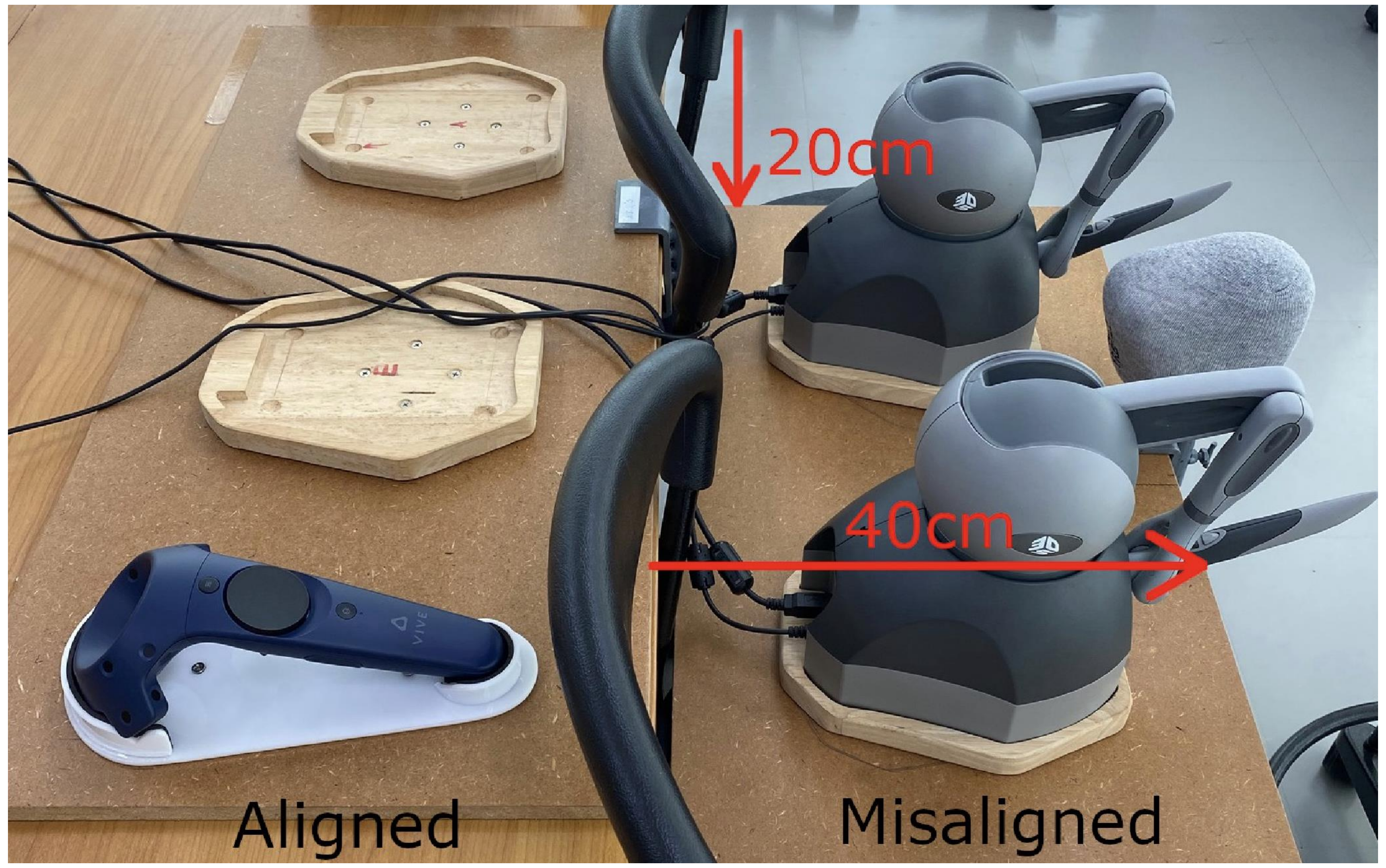


Bi-Manual Dental Simulator

HMD: Stereo Vision & Hand-Tool Alignment

- Effect of HMD VR
  - *3D rendering*: stereo 3D & monoscopic 3D
  - *Hands & tools*: aligned & misaligned

Group 1: Stereoscopic 3D & hand-tool alignment	**Group 2**: Monoscopic 3D & hand-tool alignment	**Group 3**: Stereoscopic 3D & hand-tool misalignment	**Group 4**:Monoscopic 3D & hand-tool misalignment

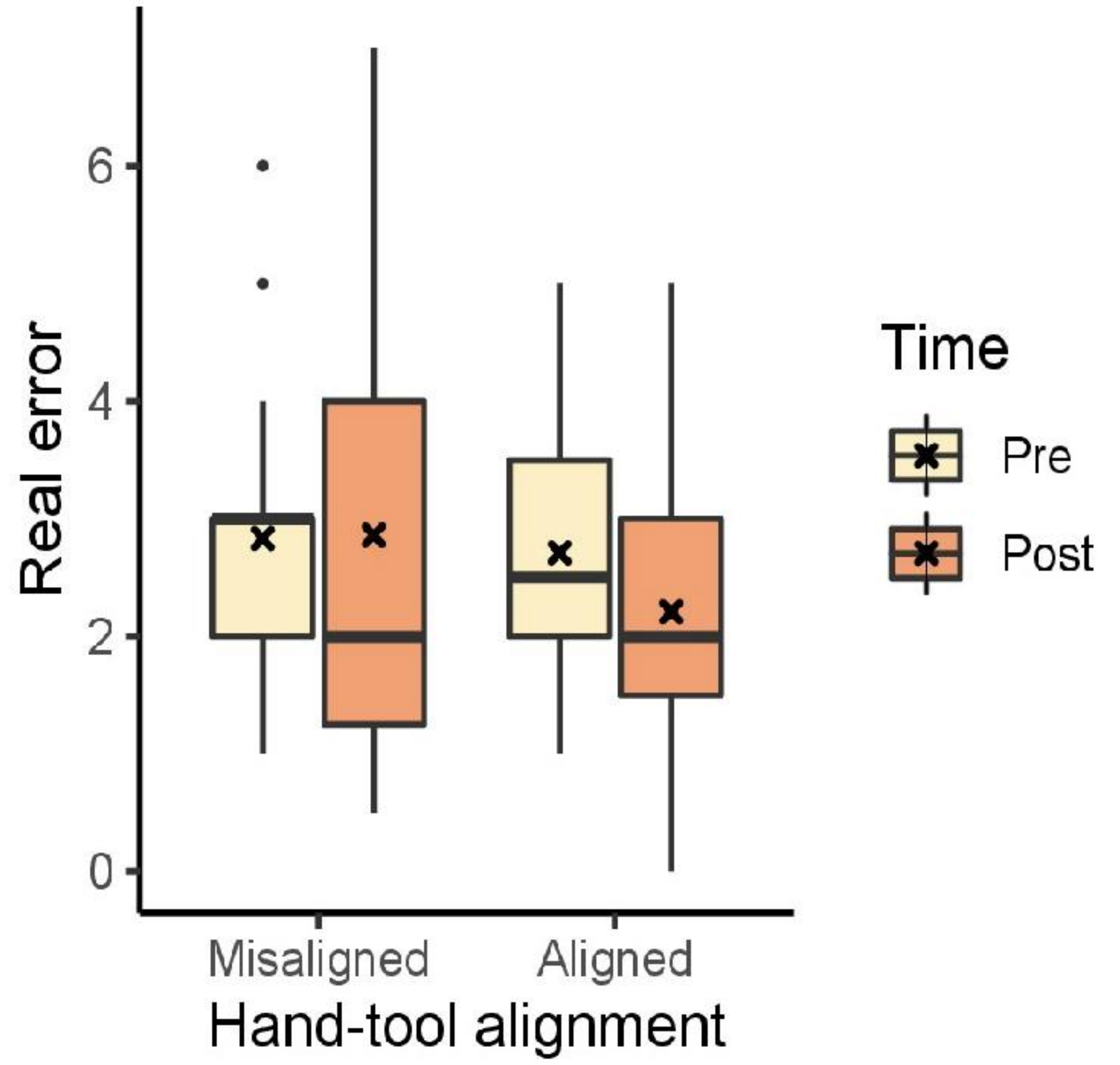


- Performance and learning effect
  - *Real* = plastic teeth
  - *Virtual* = simulator score

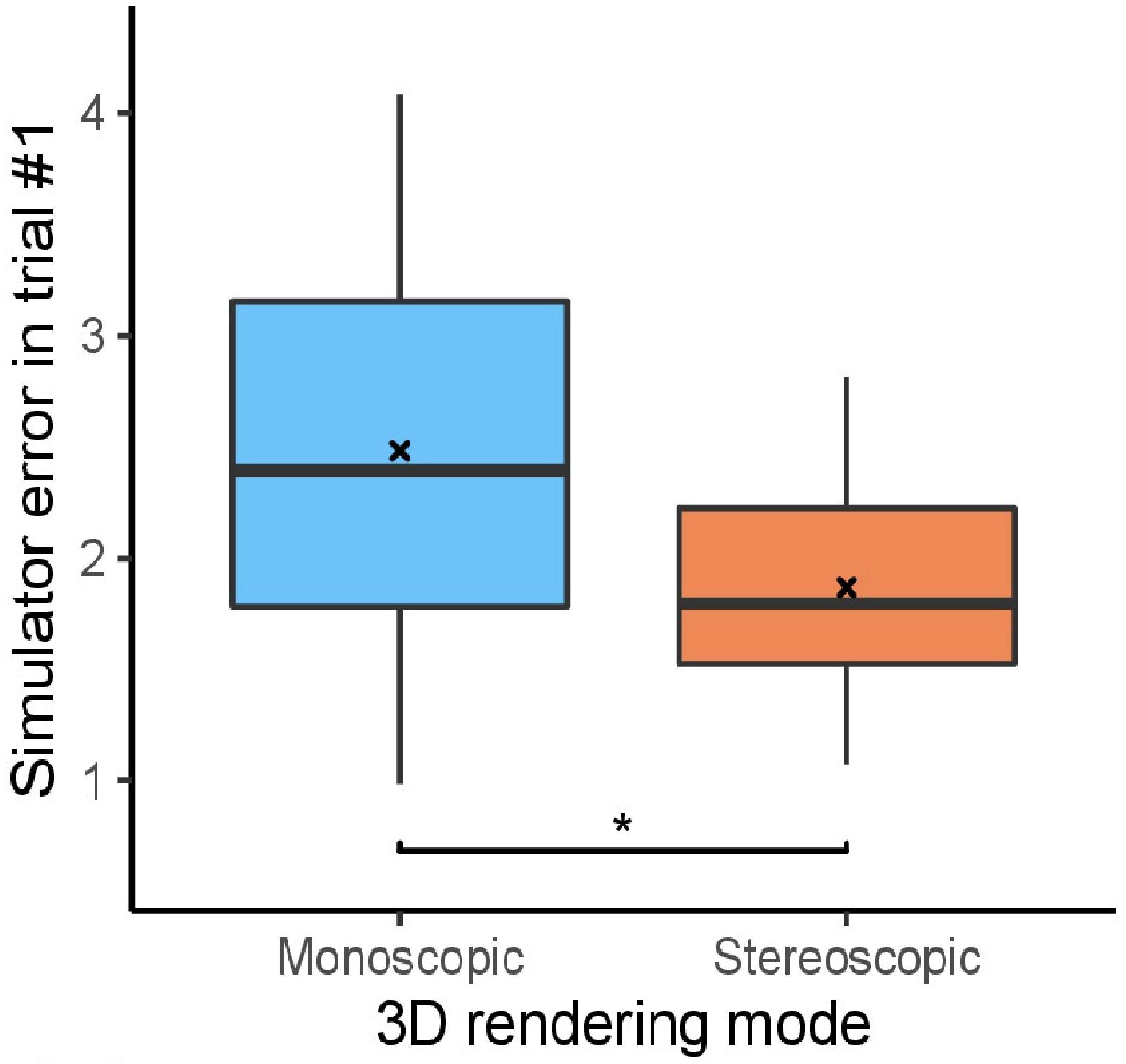
HMD: Stereo Vision & Hand-Tool Alignment

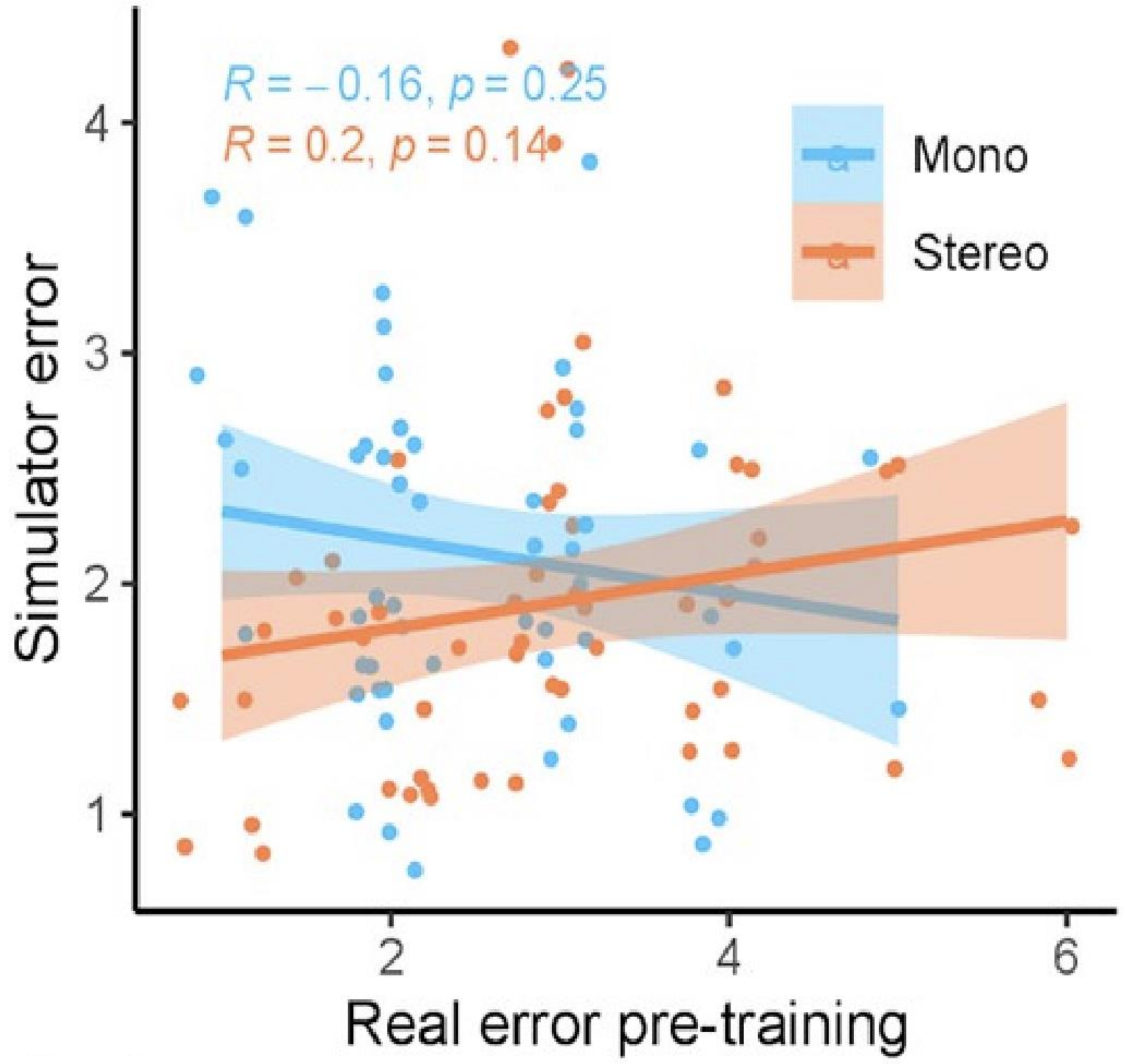
HMD: Stereo Vision & Hand-Tool Alignment

- Hand-tool alignment improves learning effect
  - By real-world measures



- Stereo 3D improves skill transfer





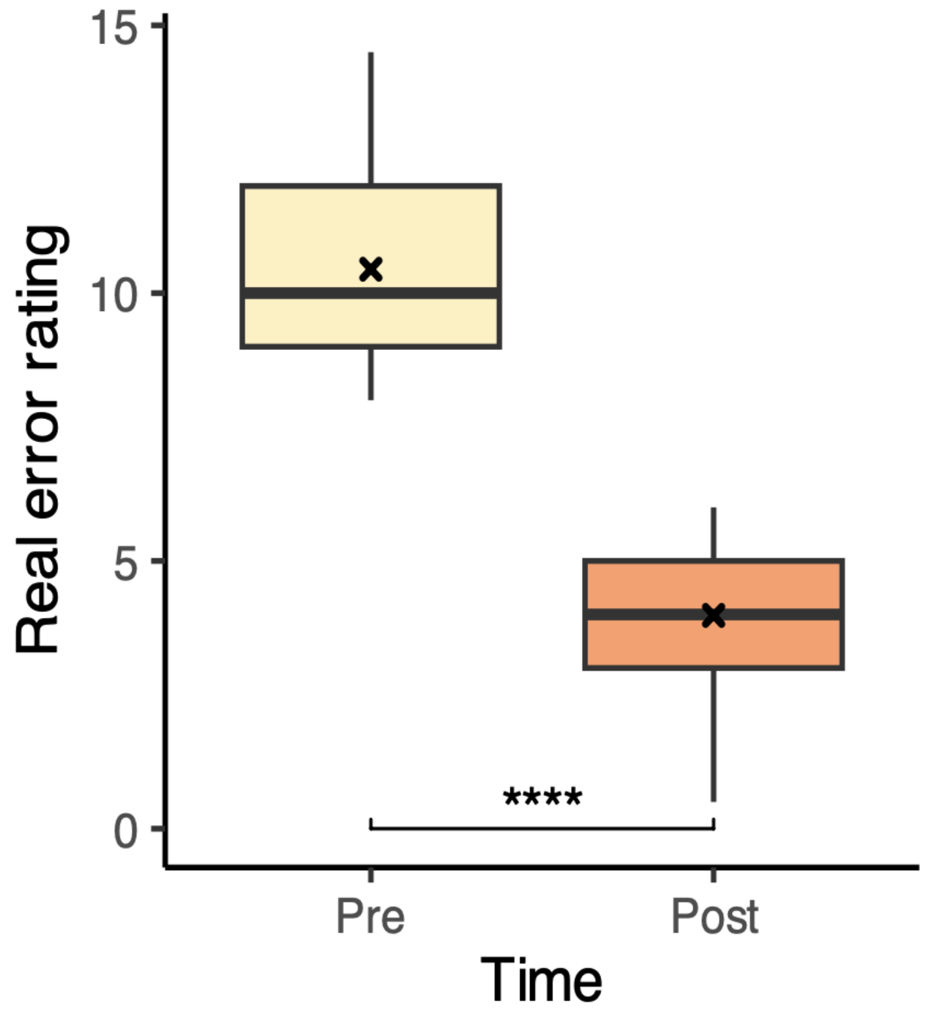
Gaze Analysis of Dental Students

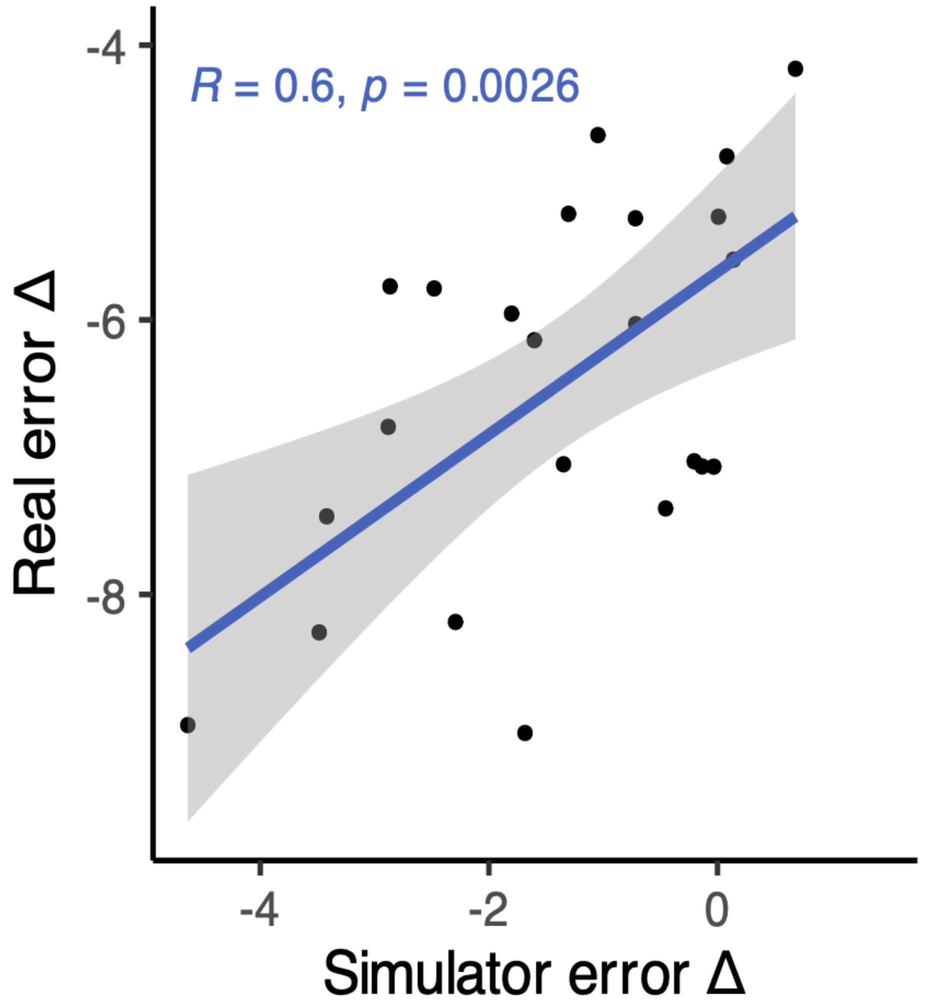
- Can gaze behavior predict performance & learning?
- Custom eye tracking integration
  - Fast: 120 Hz
  - Accurate: 1.2° error
- Custom VR zoom feature
- Complex mirrored gaze on upper jaw

Gaze Analysis of Dental Students

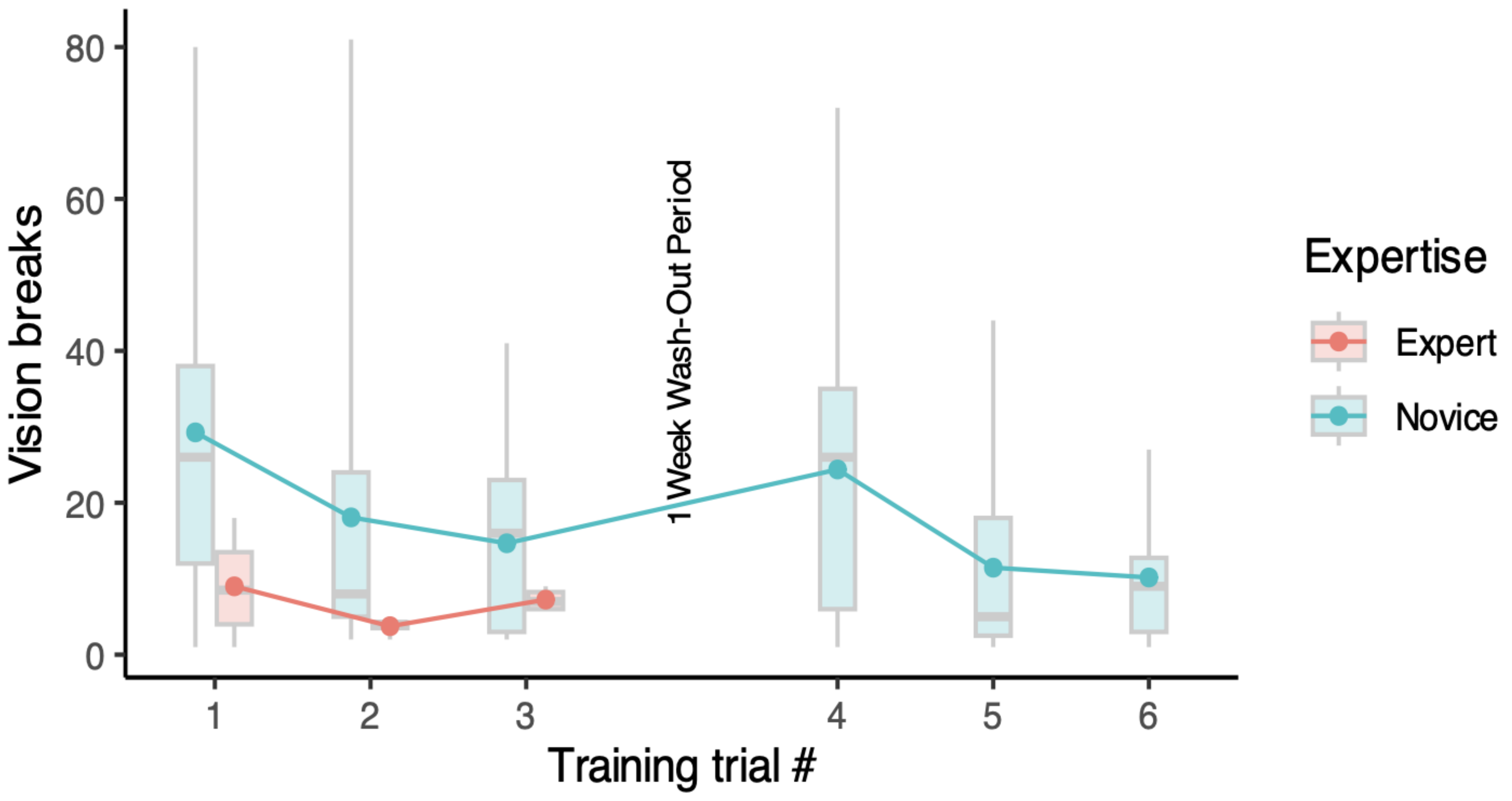
Gaze Analysis of Dental Students

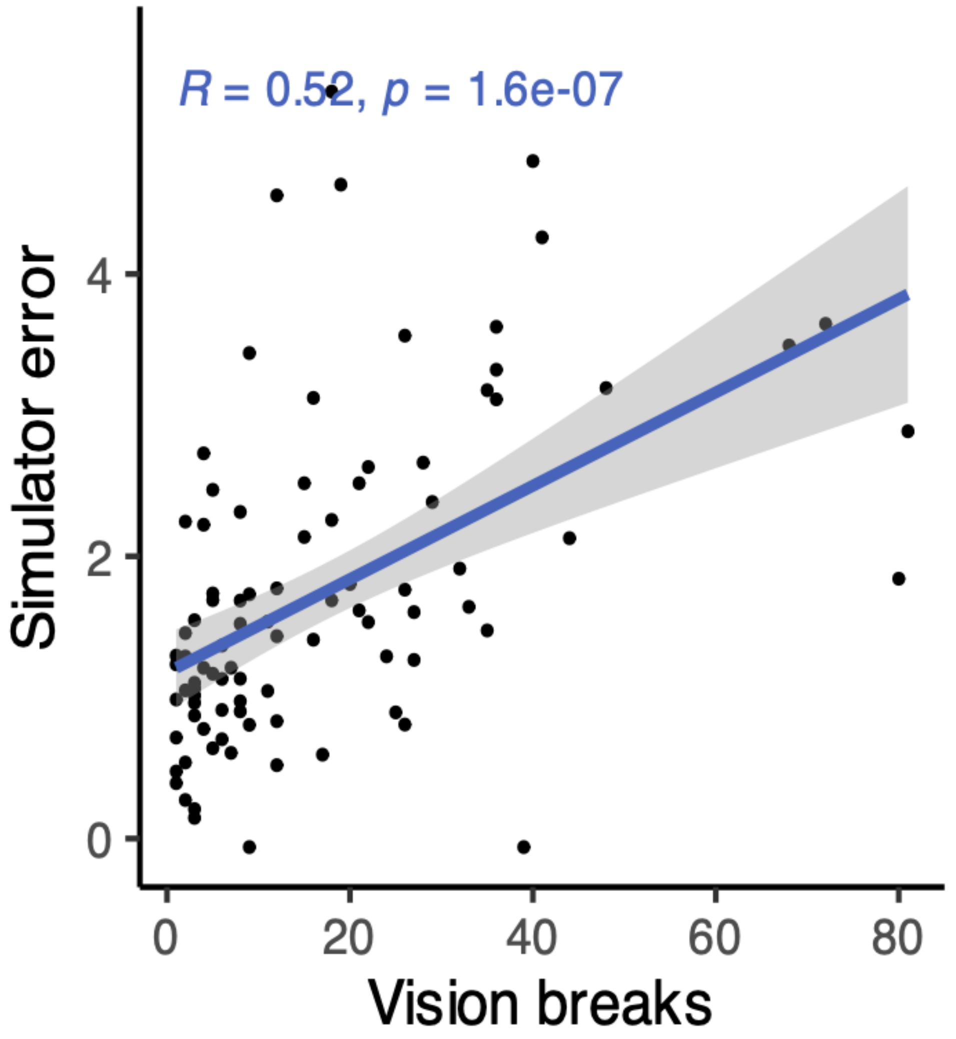
- Learning effectiveness high

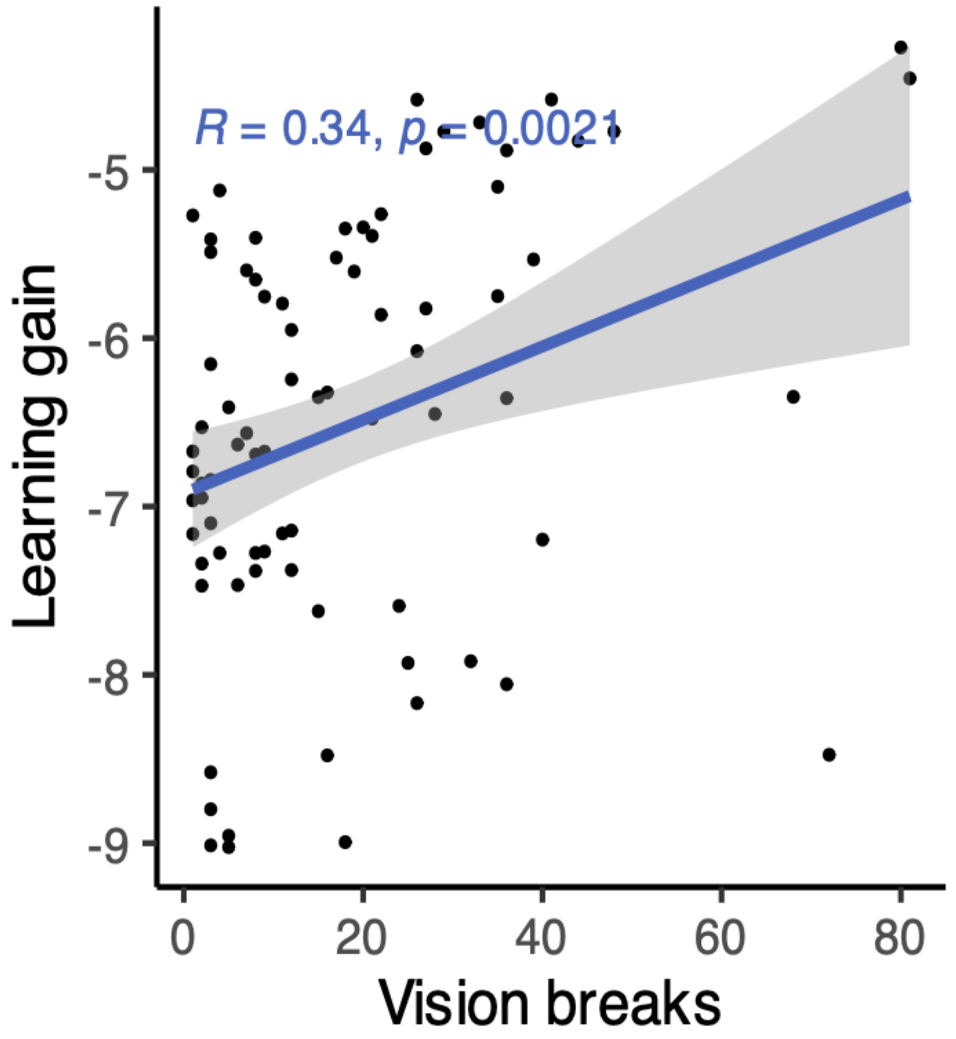




- Formulated novel gaze-based metrics
  - Consistency of vision: vision breaks







Conclusions

- Intersection-free simulation with modular collision responses
- Fully stepless material removal
- Novel simulation system for rigid 6DOF tools
- First high-force surgical VR simulator
  - Automated VR-haptic registration
- Simulators' learning efficacy objectively proven
  - Wide approval of usefulness & realism by dozens of surgeons & students

Future Works

- Effect of real-time feedback based on my gaze-metrics
- Simulate flexible tools, such as files for root-canals
  - Soft tissue deformation & cutting
- Compare with more expensive collision responses
  - E.g. constraints with global solvers

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3. **Kaluschke**, M., Yin, M.S., Haddawy, P., Srimaneekarn, N., Saikaew, P., and Zachmann, G. (2021). A Shared Haptic Virtual Environment for Dental Surgical Skill Training. In *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pages 347–352, Lisbon, Portugal. IEEE
4. **Kaluschke**, M., Yin, M.S., Haddawy, P., Suebnukarn, S., and Zachmann, G. (2022). The Impact of 3D Stereopsis and Hand-Tool Alignment on Effectiveness of a VR-based Simulator for Dental Training. In *2022 IEEE 10th International Conference on Healthcare Informatics (ICHI)*, pages 449–455, Rochester, MN, USA. IEEE
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6. **Kaluschke**, M., Yin, M.S., Haddawy, P., Suebnukarn, S., and Zachmann, G. (2023). The Effect of 3D Stereopsis and Hand-Tool Alignment on Learning Effectiveness and Skill Transfer of a VR-based Simulator for Dental Training. *PLOS ONE*, 18(10):e0291389
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Publications (Coauthor)

1. Weyhe, D., Uslar, V., Weyhe, F., **Kaluschke**, M., and Zachmann, G. (2018). Immersive Anatomy Atlas — Empirical Study Investigating the Usability of a Virtual Reality Environment as a Learning Tool for Anatomy. *Frontiers in surgery*, 5(73):73

2. Ziadeh, T., Perret, J., **Kaluschke**, M., Knopp, S., and Lorenz, M. (2020). Review of Haptic Rendering Techniques for Hip Surgery Training. In *EuroVR 2020 Application, Exhibition & Demo Track: Proceedings of the Virtual EuroVR Conference*, number 381 in VTT Technology, pages 29–39. VTT Technical Research Centre of Finland

3. Pelliccia, L., Lorenz, M., Heyde, C.-E., **Kaluschke**, M., Klimant, P., Knopp, S., Schleifenbaum, S., Rotsch, C., Weller, R., Werner, M., Zachmann, G., Zajonz, D., and Hammer, N. (2020). A Cadaver-Based Biomechanical Model of Acetabulum Reaming for Surgical Virtual Reality Training Simulators. *Nature Scientific Reports*, 10(1):145458

4. Gloy, K., Weyhe, P., Nerenz, E., **Kaluschke**, M., Uslar, V., Zachmann, G., and Weyhe, D. (2022). Immersive Anatomy Atlas: Learning Factual Medical Knowledge in a Virtual Reality Environment. *Anatomical Sciences Education*, 15(2):360–368

Immersive Medical VR Training Simulators with Haptic Feedback

Maximilian Kaluschke