Real-Time Haptic Cutting of High Resolution Soft Tissues

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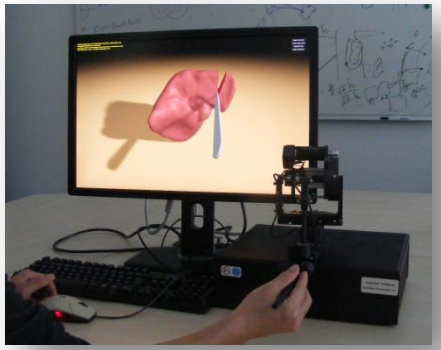
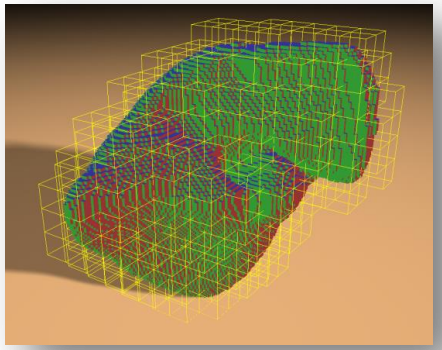
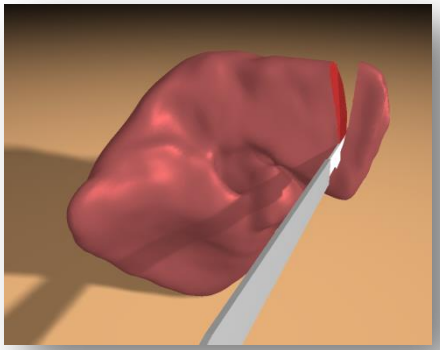
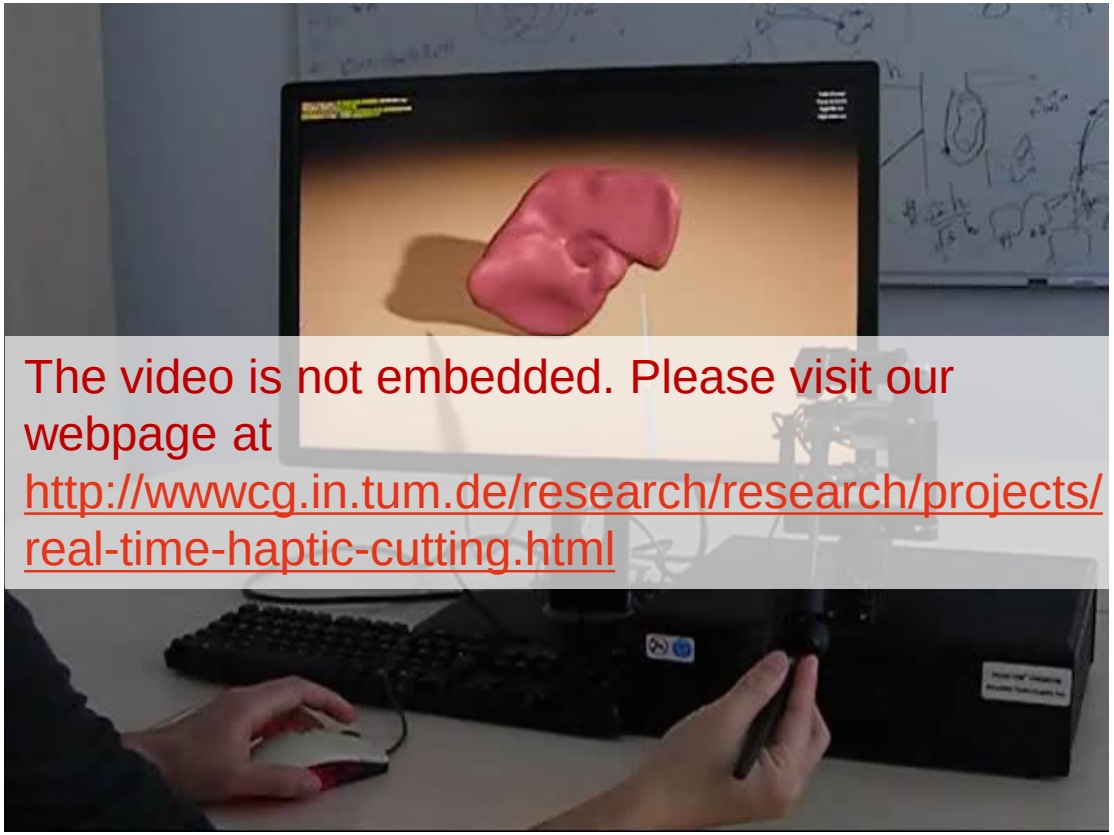






An advertiser to begin with

- Live-capture of haptic soft tissue cutting



15 fps
+ FE deformation
+ Collision detection
+ Cutting

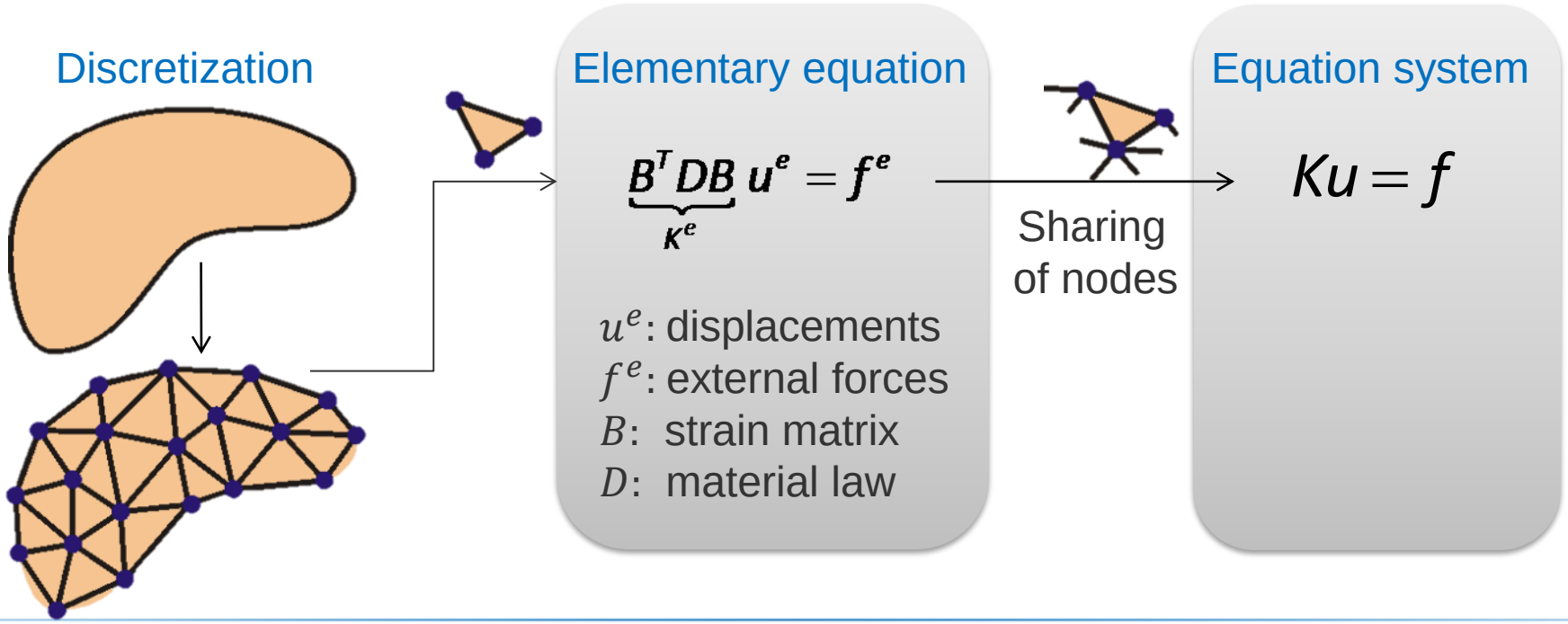
Resolution: 82×83×101
Triangles: 59 k
Finite elements: 170 k
Simulation DOFs: 3 k

Finite element (FE) simulation of elasticity

1) Discretize the object into elements
2) Build elementary equations $K^e u^e = f^e$
3) Assemble a linear system of equations $Ku = f$

Preprocessing

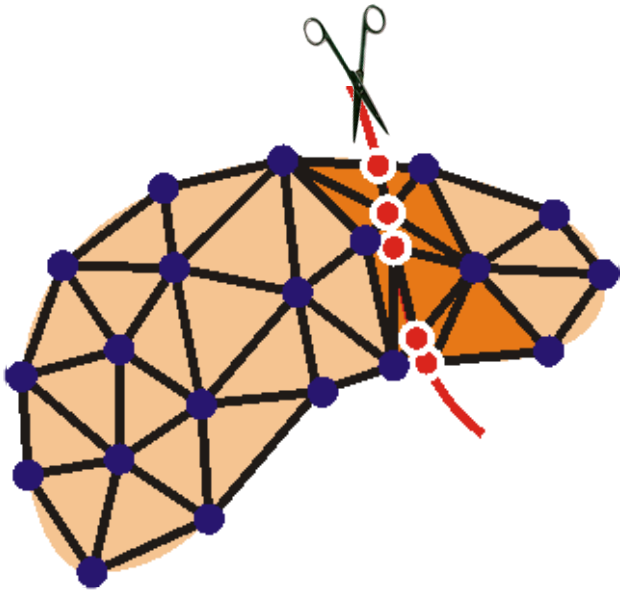
4) In each simulation step, solve for the displacement u



Virtual cutting particularly requires

1) Split elements which are touched by the scalpel
2) Re-build elementary equations $K^e u^e = f^e$
3) Re-assemble a linear system of equation $Ku = f$
4) In each simulation step, solve for the displacement u

Real-time processing



2D illustration of cutting

Challenges

Computational efficiency:

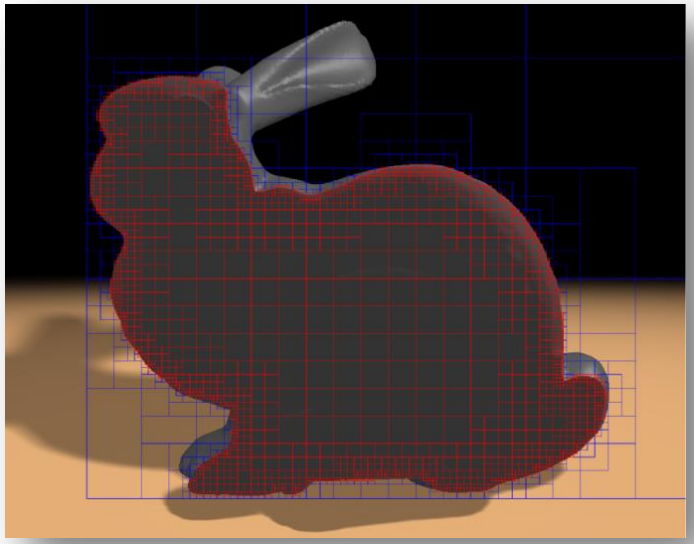
- Performing all geometrical and numerical modifications in real-time

Numerical stability:

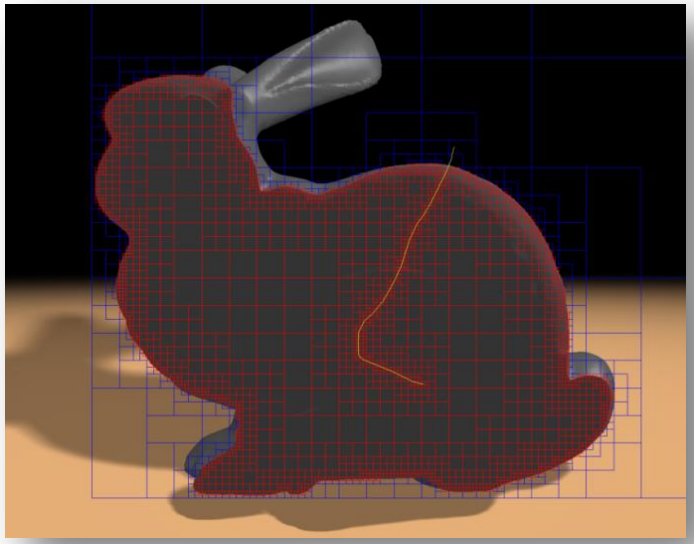
- Avoiding ill-shaped elements (e.g., needles, slivers) which are numerically unstable

The basic idea

- Semi-regular hexahedral elements
  - Efficient splitting using octree subdivision (1 -> 2^3)
  - Stable splitting: no ill-shaped elements



Initial octree

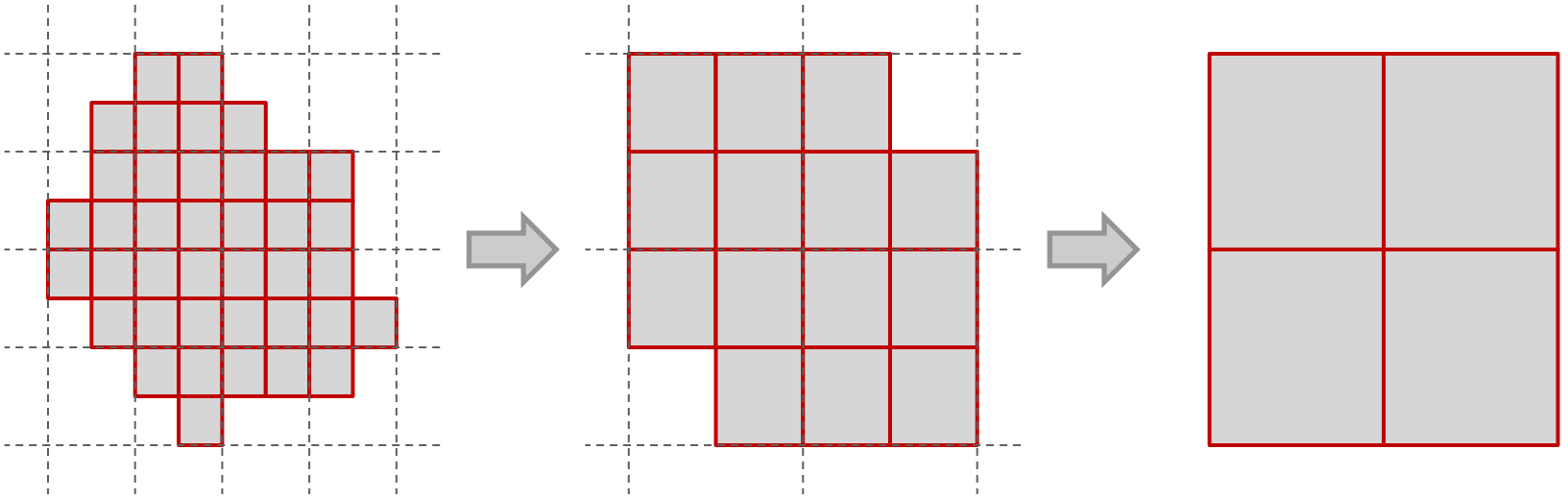


Refined octree

[Dick et al. 2011]

The basic idea

- Semi-regular hexahedral elements
  - Efficient splitting using octree subdivision (1 -> 2^3)
  - Stable splitting: no ill-shaped elements
  - Efficient hierarchy construction based on the hexahedral grid (2^3 -> 1)

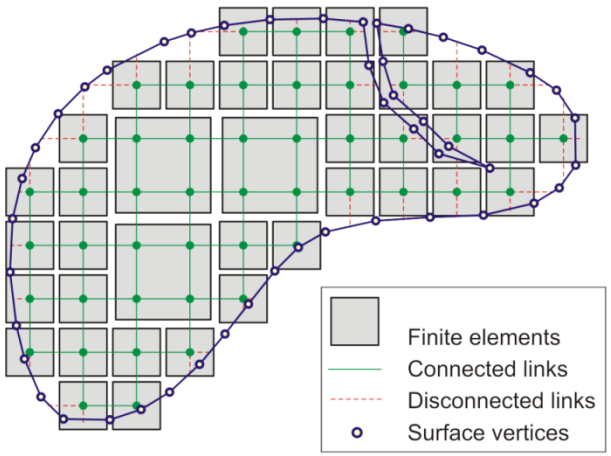


Level 0 Level 1 Level 2

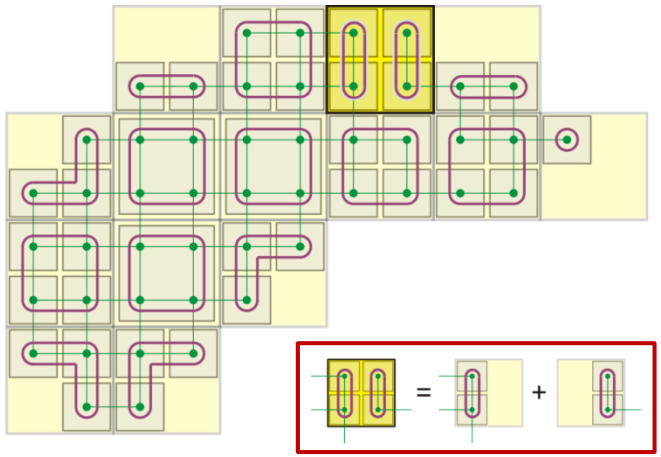
[Dick et al. 2011]

Composite finite elements (CFEs)

- To reduce the number of simulation degrees of freedom
- Composite finite elements: approximate a high resolution finite element discretization by a small set of coarser elements
  - Composite elements are duplicated by analyzing the topology



a. Linked octree representation



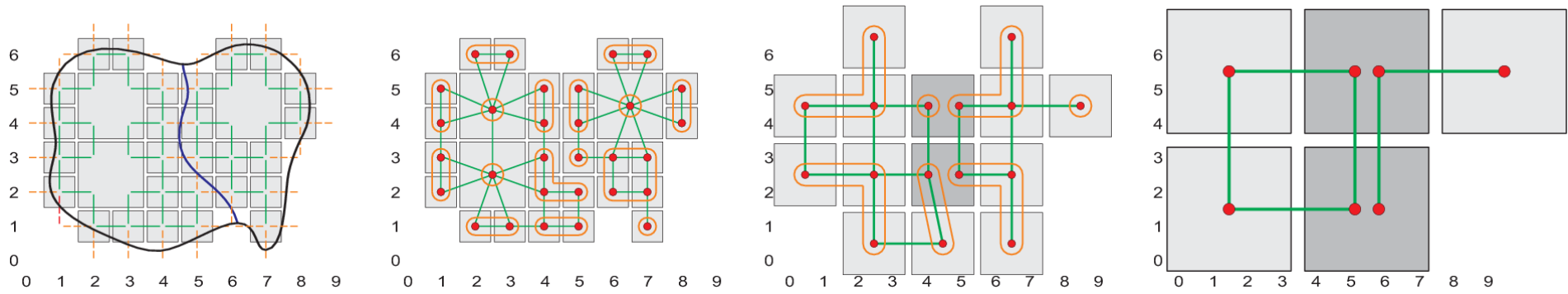
Duplicated elements

b. Composite finite elements

[Wu et al. 2011]

Composite finite elements (CFEs)

- To reduce the number of simulation degrees of freedom
- Composite finite elements: approximate a high resolution finite element discretization by a small set of coarser elements
  - Composite elements are duplicated by analyzing the topology
  - Iteratively constructed by exploring the hierarchy of grids

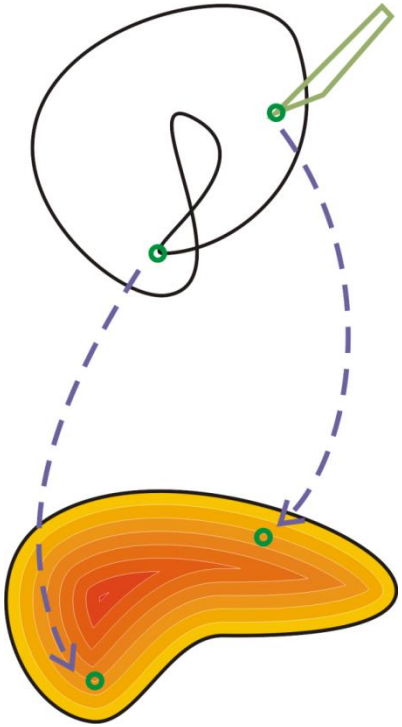


Iterative construction of composite elements

[Wu et al. 2011]

Collision detection for CFEs

- Broad phase
  - In deformed configuration
  - Detect potentially overlapping vertex-composite element pairs
- Narrow phase
  - In reference configuration
  - Interpolate penetration depth from a locally-updated distance field



Deformed configuration

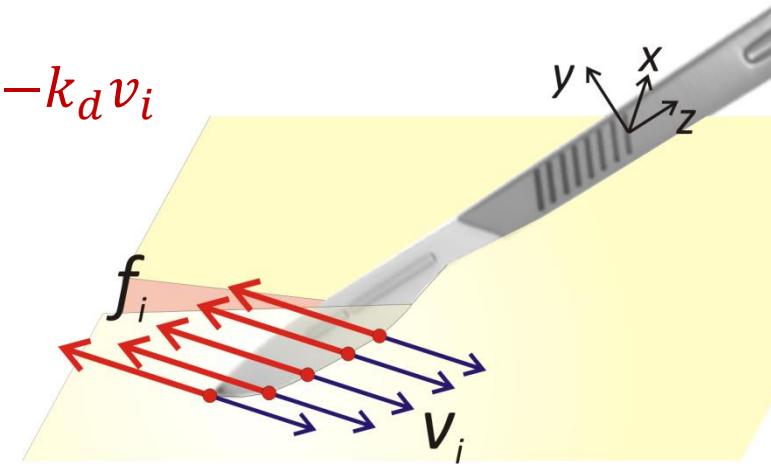
Reference configuration

- Acceleration techniques
  - Processing vertex-composite element pairs, instead of vertex-fine element pairs
  - Local distance field updating
  - Topology-aware interpolation

[Wu et al. 2013]

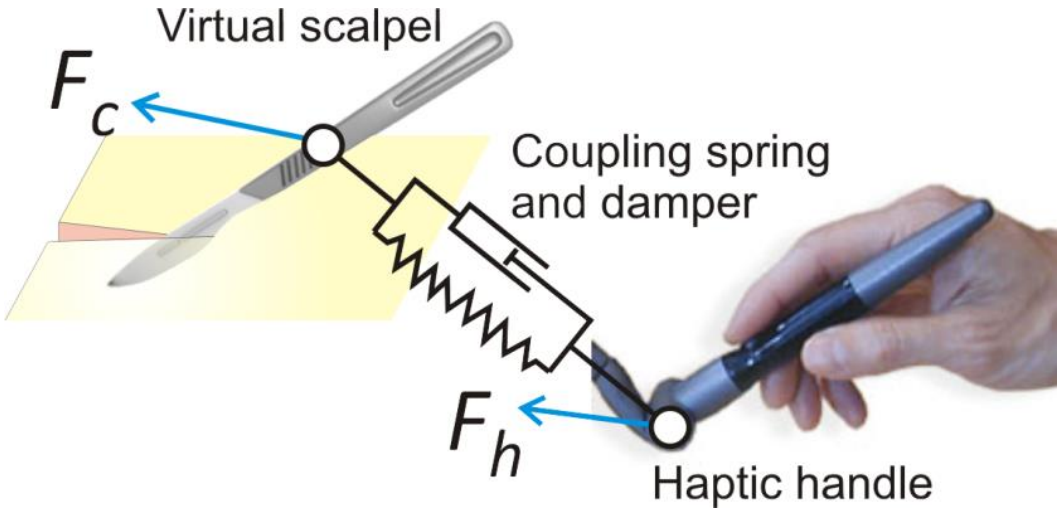
Stable haptic rendering

- Elementary cutting force model $f_i = -k_d v_i$
  - k_d, a damping coeffcient
  - v_i, the velocity of the sampling point



- Total cutting force $F_c = \sum_i f_i$

- Stable haptic rendering using virtual coupling

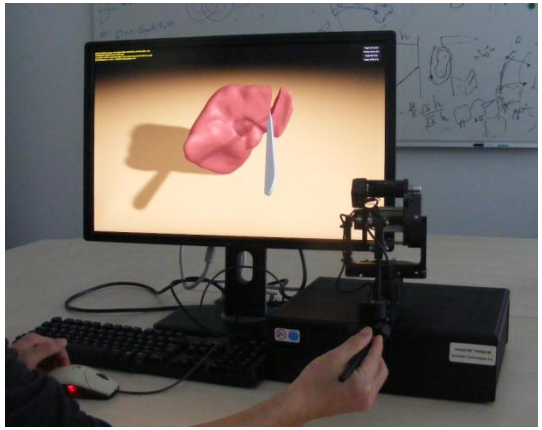


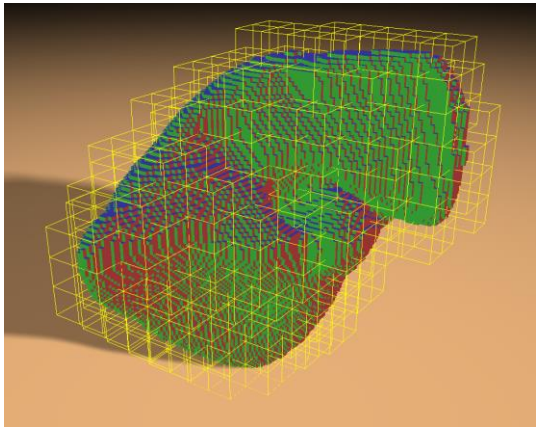
[Wu et al. 2010]

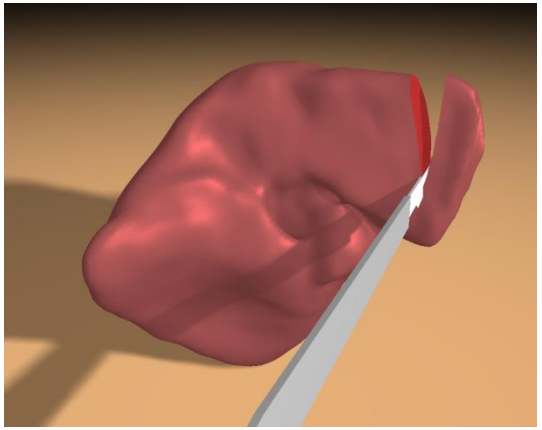
Results

- Collision detection + FEM deformation: 37 fps
- Per-cut updating: 38 ms

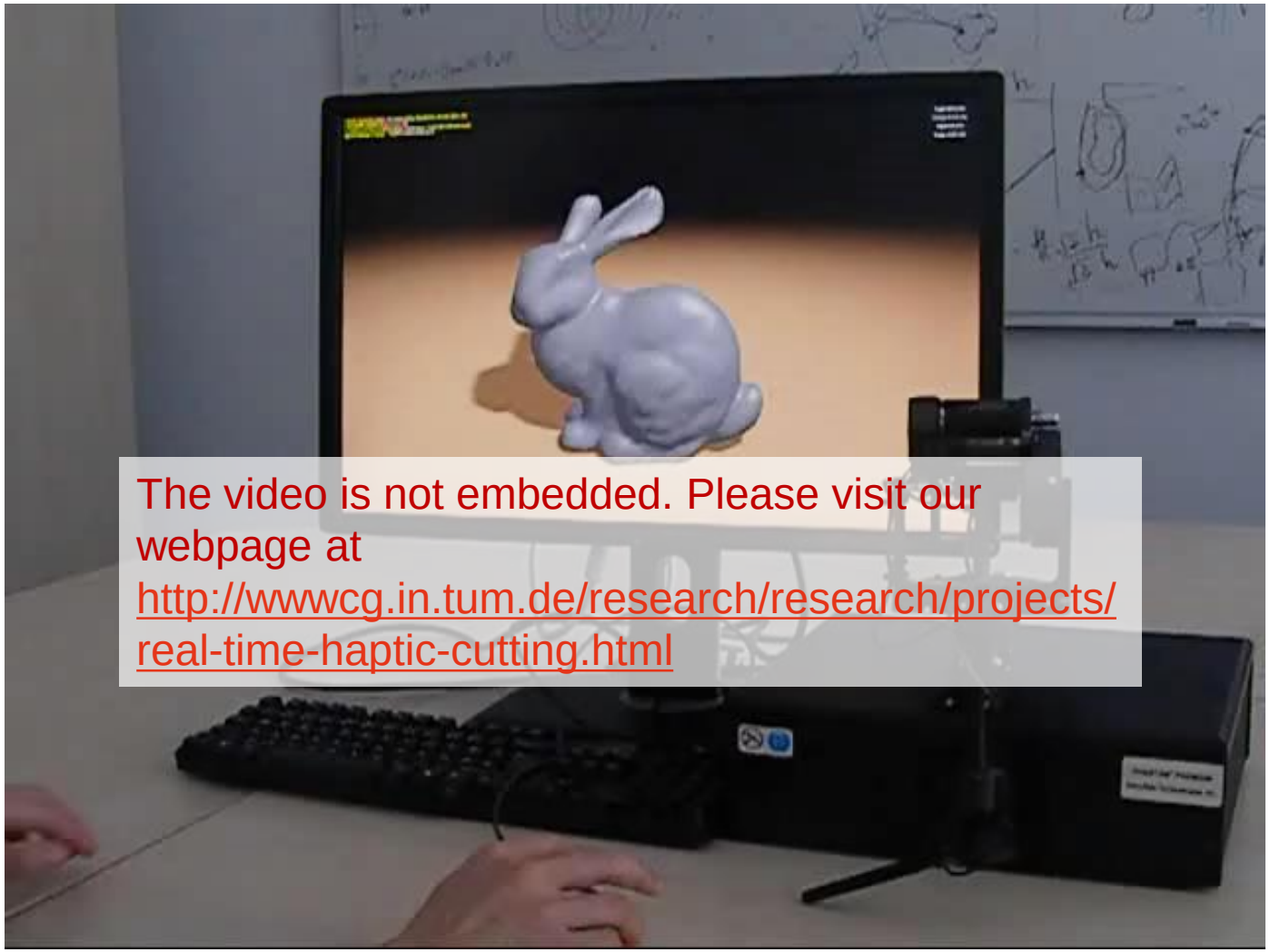
Hexahedral grid	Com-position	# Sim. DOFs	# Tris	Timing (Speedup) Col. Det.	FEM	Total
82×83×101	8^3 --> 1	2,928	59 k	3.2 ms (58.4 ×)	23.3 ms (103.7 ×)	26.5 ms (98.2 ×)







Results - Demo



Summary

- Real-time haptic cutting of high-resolution soft tissues
  - 15 simulation frames per second on a resolution of 82×83×101
  - Achieved by using semi-regular hexahedral grids
  - With a set of efficient algorithms

- Future work
  - Evaluate the simulator in specific medical scenarios
  - Physically accurate modeling of scalpel-tissue contacts

Thank you for your attention.

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Notes

- This is the following paper presented at the NextMed / MMVR21 Conference, February 19 - 22, 2014, Manhattan Beach, California
  - [Wu et al. 2014] Real-Time Haptic Cutting of High Resolution Soft Tissues, J. Wu, R. Westermann, C. Dick, Studies in Health Technology and Informatics (Proc. Medicine Meets Virtual Reality 2014), 196:469-475, 2014

- Please refer to the references for more technical details
  - [Dick et al. 2011] A Hexahedral Multigrid Approach for Simulating Cuts in Deformable Objects, C. Dick, J. Georgii, R. Westermann, IEEE Transactions on Visualization and Computer Graphics 17(11):1663-1675, 2011
  - [Wu et al. 2011] Interactive High-Resolution Boundary Surfaces for Deformable Bodies with Changing Topology, J. Wu, C. Dick, R. Westermann, Workshop on Virtual Reality Interaction and Physical Simulation (VRIPHYS) 2011
  - [Wu et al. 2013] Efficient Collision Detection for Composite Finite Element Simulation of Cuts in Deformable Bodies, J. Wu, C. Dick, R. Westermann, The Visual Computer (Proc. Computer Graphics International 2013), 29(6-8):739-749, 2013
  - [Wu et al. 2010] Toward stable and realistic haptic interaction for tooth preparation simulation, J. Wu, D. Wang, C.C.L. Wang, Y. Zhang, ASME Transactions - Journal of Computing and Information Science in Engineering, 10(2):021007:1-9, 2010