Physically-based Simulation of Cuts in Deformable Bodies

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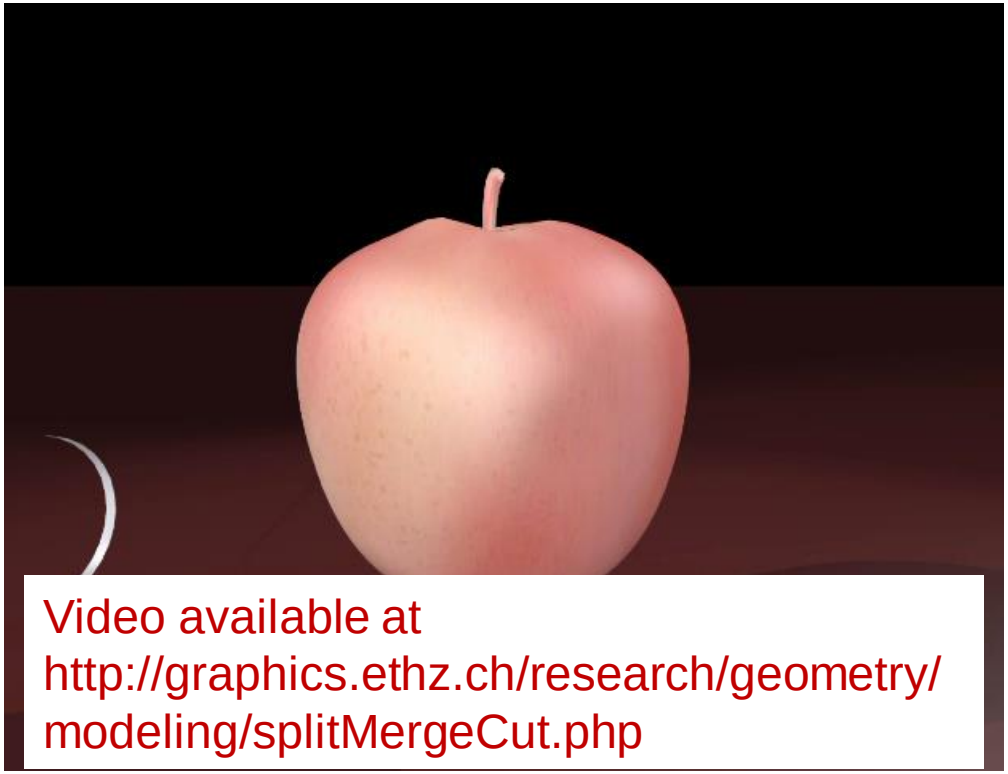
Virtual Cutting in Computer Animation

- Applications: computer games, visual effects



Meshfree method

[Steinemann et al. 2006]

Virtual Cutting in Computer Animation

- Applications: computer games, visual effects

Polyhedral finite element method

[Wicke et al. 2007]

Virtual Cutting in Surgery Simulation

- Applications: surgery skill training, pre-operative planning

Surgery simulation on a patient data set

[Courtecuisse et al. 2010]

SHACRA team at INRIA

Motivation of the Report

- Provide an overview of recent virtual cutting techniques

Reference	Geometry	Deformation	Solver	Scenario	Remark
Bielser et al. [BMG99, BG00, BGTG04]	Tet., refinement	Mass-spring	Explicit/Semi-implicit	Interactive	Basic tet. refinement
Cotin et al. [CDA00]	Tet., deletion	Tensor-mass	Explicit	Interactive	Hybrid elastic model
Mor & Kanade [MK00]	Tet., refinement	FEM	Explicit	Interactive	Progressive cutting
Nienhuys et al. [NFvdS00, NFvdS01]	Tet., boundary splitting/snapping	FEM	Static (CG solver)	Interactive	FEM with a CG solver
Bruyns et al. [BSM*02]	Tet., refinement	Mass-spring	Explicit	Interactive	An early survey
Steinemann et al. [SHGS06]	Tet., refinement + snapping	Mass-spring	Explicit	Interactive (Fig. 13 a)	Hybrid cutting
Chentanez et al. [CAR*09]	Tet., refinement	FEM	Implicit (CG solver)	Interactive (Fig. 13 d)	Needle insertion
Courtecuisse et al. [CJA*10, CAK*14]	Tet., deletion/refinement	FEM	Implicit (CG solver)	Interactive (Fig. 13 c,e)	Surgery applications
Molino et al. [MBF04]	Tet., duplication	FEM	Mixed explicit/implicit	Offline	Basic virtual node algorithm
Sifakis et al. [SDF07]	Tet., duplication	FEM		Offline (Fig. 12 a)	Arbitrary cutting
Jeřábková & Kuhlen [JK09]	Tet.	XFEM	Implicit (CG solver)	Interactive	Introduction of XFEM
Turkiyyah et al. [TKAN09]	Tri.	2D-XFEM	Static (direct solver)	Interactive	XFEM with a direct solver
Kaufmann et al. [KMB*09]	Tri./Quad.	2D-XFEM	Semi-implicit	Offline (Fig. 12 c)	Enrichment textures
Frisken-Gibson [FG99]	Hex., deletion	ChainMail	Local relaxation	Interactive	Linked volume
Jeřábková et al. [JBB*10]	Hex., deletion	CFEM		Interactive	CFEM
Dick et al. [DGW11a]	Hex., refinement	FEM	Implicit (multigrid)	Offline/Interactive (Fig. 12 d)	Linked octree, multigrid solver
Seiler et al. [SSSH11]	Hex., refinement	FEM	Implicit	Interactive	Octree, surface embedding
Wu et al. [WDW11, WBWD12, WDW13]	Hex., refinement	CFEM	Implicit (multigrid)	Interactive (Fig. 13 b, f)	Collision detection for CFEM
Wicke et al. [WBG07]	Poly., splitting	PFEM	Implicit	Offline (Fig. 12 b)	Basic polyhedral FEM
Martin et al. [MKB*08]	Poly., splitting	PFEM	Semi-implicit	Offline	Harmonic basis functions
Pauly et al. [PKA*05]	Particles, transparency	Meshfree	Explicit	Offline	Fracture animation
Steinemann et al. [SOG06]	Particles, diffraction	Meshfree		Offline/Interactive (Fig. 12 e)	Splitting fronts propagation
Pietroni et al. [PGCS09]	Particles, visibility	Meshfree		Interactive	Splitting cubes algorithm

Motivation of the Report

- ❖ Provide an overview of recent virtual cutting techniques
- Share our experience and understanding on this topic

Video available at
http://wwwcg.in.tum.de/research/research/publications/2011/a-hexahedral-multigrid-approach-for-simulating-cuts-in-deformable-objects.html

Hexahedral finite element method on an octree grid

Armadillo:
500k elements,
10 seconds per frame

[Dick et al. 2011]

Motivation of the Report

- ❖ Provide an overview of recent virtual cutting techniques
- Share our experience and understanding on this topic

Haptic cutting of
high-resolution soft tissues

Liver:
15 fps
3k DOFs (170k elements)

[Wu et al. 2014]

Motivation of the Report

- ❖ Provide an overview of recent virtual cutting techniques
- Share our experience and understanding on this topic
- Discuss and identify future research problems
  - How to realistically simulate various cutting effects?

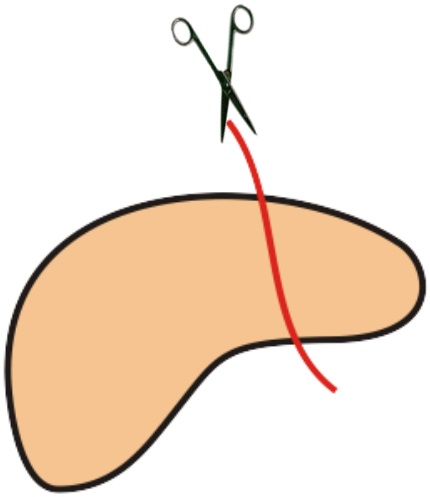
Cutting in hospitals

Cutting in kitchens

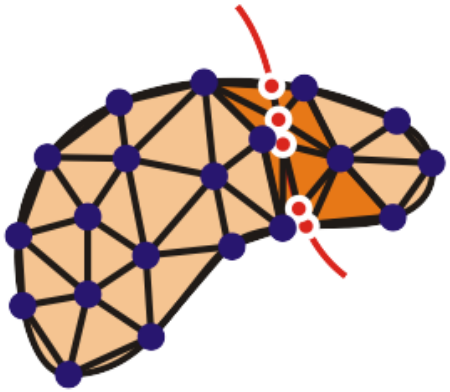
Images removed due to copyright

Virtual Cutting from a Computational Point of View

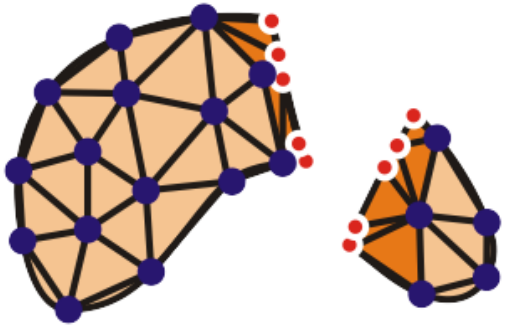
- Incorporation of cuts into the computational model
- Deformable body simulation



2D illustration of cutting process



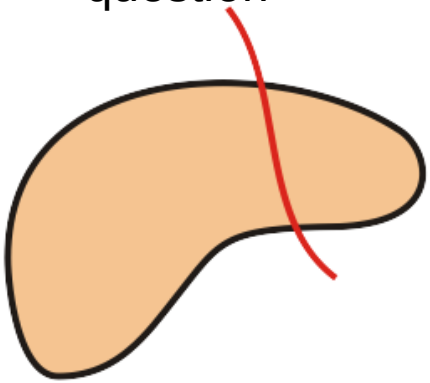
Mesh-based modeling of cuts



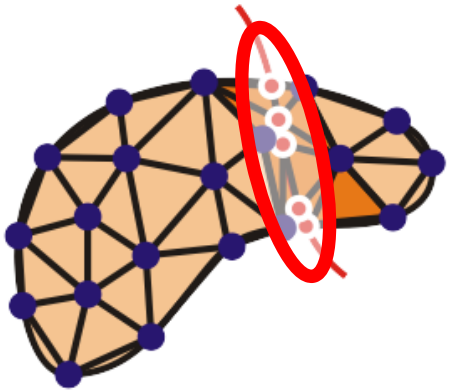
FE simulation of deformation

Virtual Cutting from a Computational Point of View

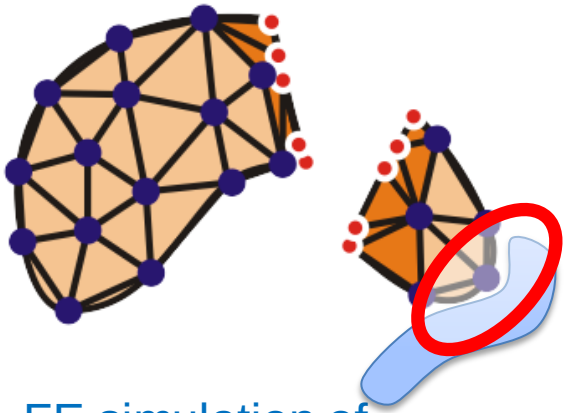
- Incorporation of cuts into the computational model
- Deformable body simulation
  - Detection and handling of collisions
    - Collision detection: STAR by Teschner et al. 2005
    - Realistic contact handling between a scalpel and a soft object: Open question



2D illustration of cutting process



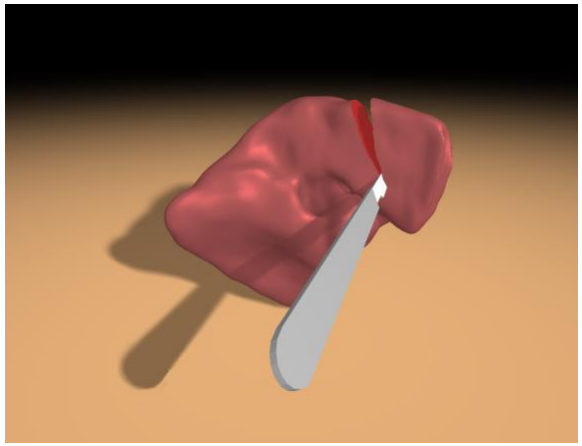
Mesh-based modeling of cuts



FE simulation of deformation

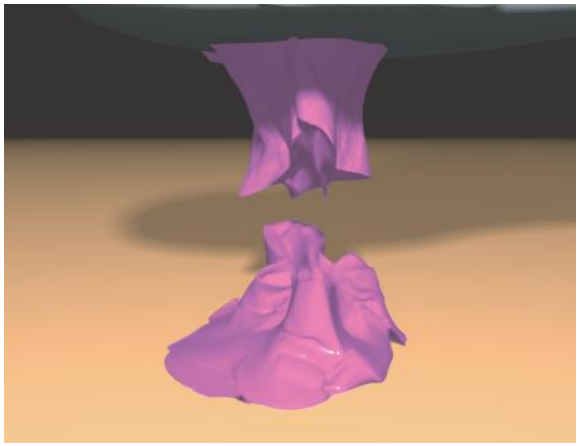
Cutting & Fracturing

- Cutting
  - Controlled separation of a physical object
  - As a result of an acutely directed force, exerted through sharp tools
- Fracturing
  - Cracking / breakage of (hard) objects
  - Under the action of stress



[Wu et al. 2014]

Cutting example

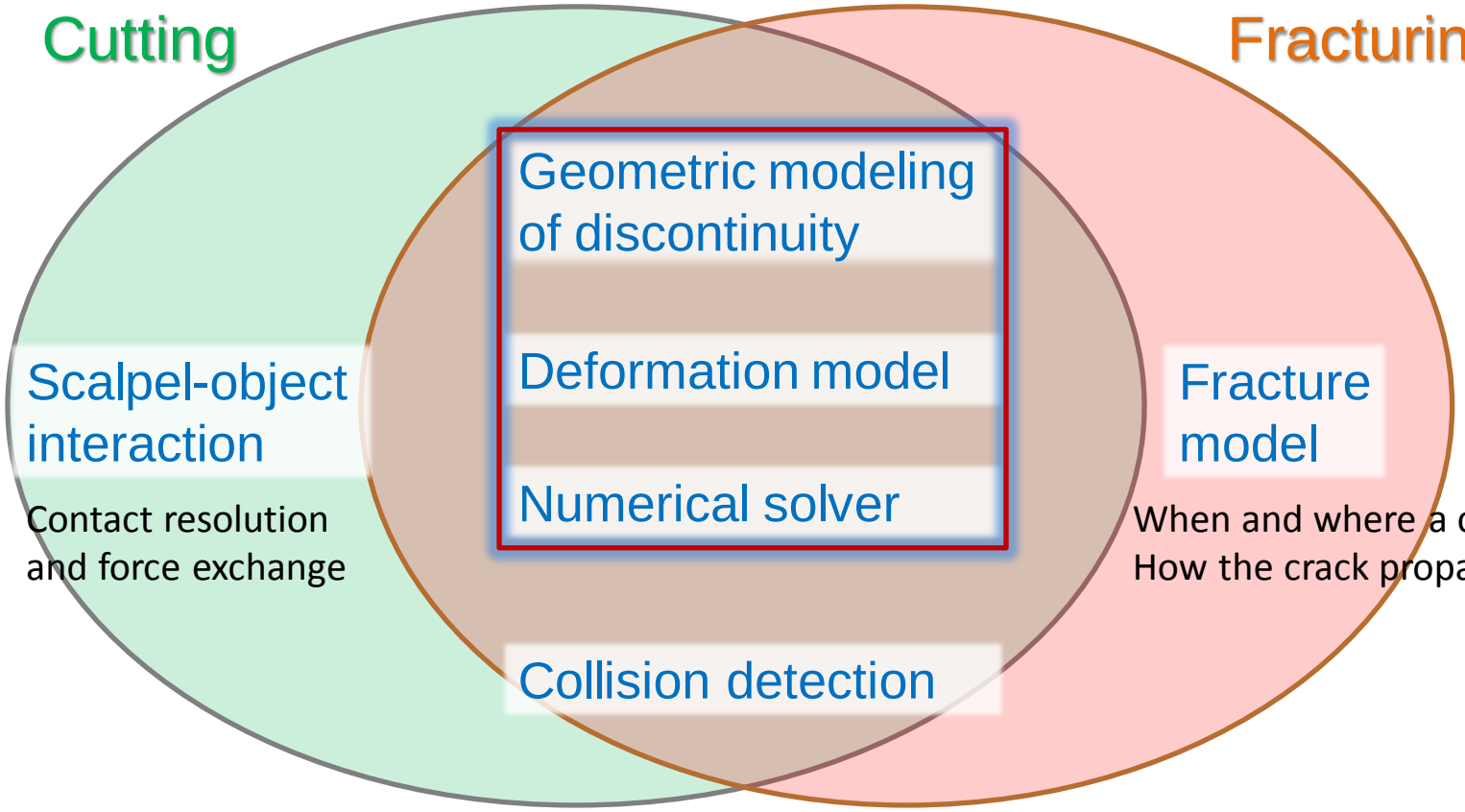


[Pauly et al. 2005]

Fracturing example

Cutting & Fracturing

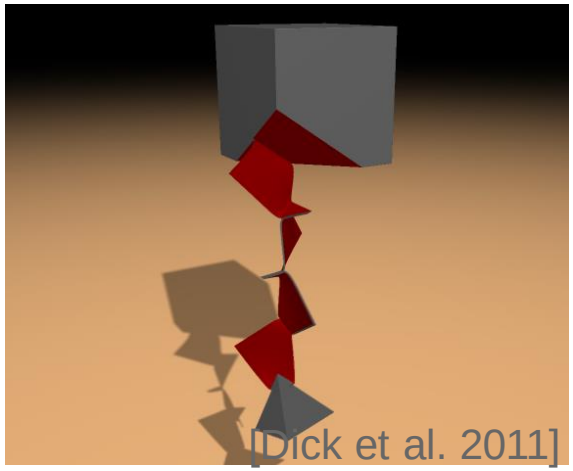
- from a computational point of view



Challenges

- Physical accuracy
  - Ability to represent arbitrarily-shaped cuts in geometry and topology
  - Ability to predicate the dynamic behavior

- Solutions:
  - Dynamic local refinement of different spatial discretizations
  - Various finite element methods


[Dick et al. 2011]

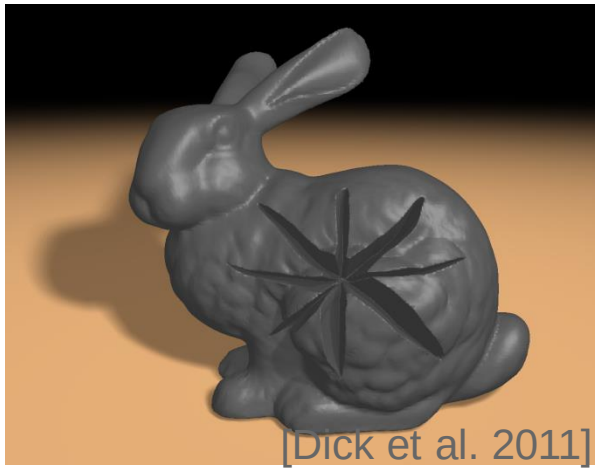

[Steinemann et al. 2006]

Examples of complicated cuts

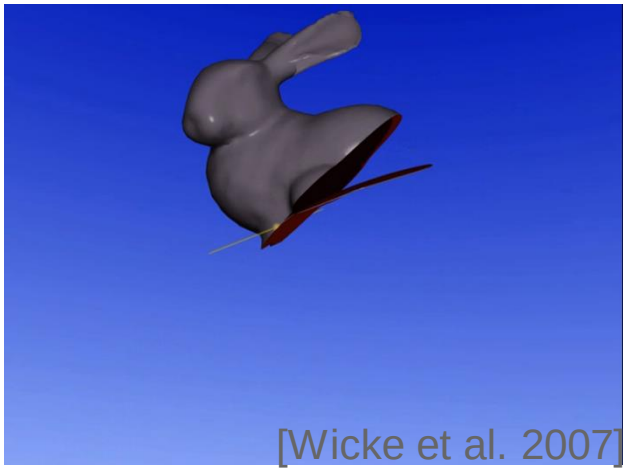
Challenges

- Physical accuracy
- Robustness
  - Numerical stability in complicated scenarios, e.g., repeated cutting, thin slicing

- Solution: to avoid ill-shaped elements, e.g., by virtual node algorithm, hexahedral discretization



Repeated cutting

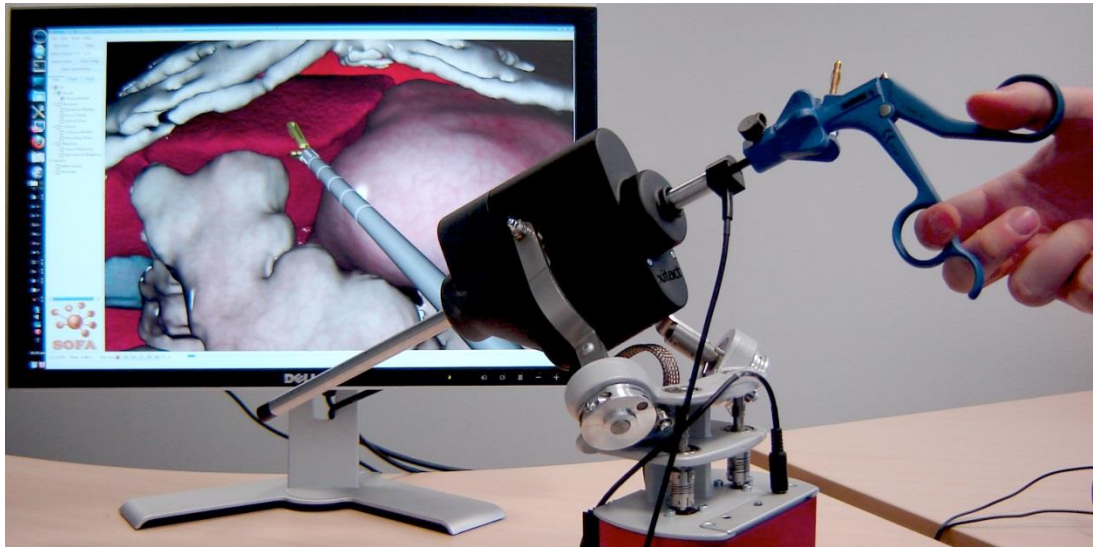


Thin slicing

Challenges

- Physical accuracy
- Robustness
- Computation efficiency

- Solutions: reducing #DOFs, efficient solvers, parallelization



Surgery simulation
with haptic feedback

[Courtecuisse et al. 2010]

Outline

follows the structure of the report

- Introduction
- Mesh-based Modeling of Cuts
- Finite Element Simulation of Virtual Cutting
- Numerical Solvers
- Meshfree Methods
- Summary & Application Study
- Discussion & Conclusion

❖ Principles and differences, not the implementation details
❖ 2D illustrations, but applicable to 3D volumetric cutting