Visual Medicine: Part Two – Advanced Topics in Visual Medicine

Soft-Tissue Simulation

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Generations of Medical Simulators

1st Generation Simulator: Geometry/Anatomy/Navigation
- Shape
- Surface & Volume
- Morphology

2nd Generation Simulator: Physics/Interaction
- Deformation & Forces
- Physical Properties

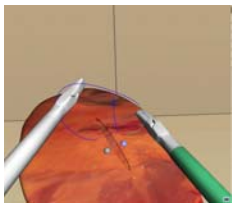
3rd Generation Simulator: Functional aspects/Physiology
- Pathology
- Function of organs and cells

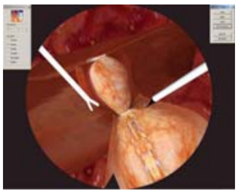
[Satava 1996,Delinquette 1998]

What we want to do: Education / Training / Assessment

Classification of training in virtual minimal invasive surgery

- Skill Level
  - Moving instruments
  - Touching locations
- (Basic) Task Level
  - Suturing
  - Clip & Cut a vessel
- Procedure Level
  - Detach and remove gallbladder
- Intervention Level
  - Cholecystectomy





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Soft Tissue Modelling and Simulation

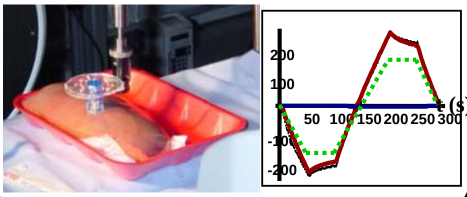
Soft tissue simulation module

- Key technology for 2nd and 3rd generation simulator
- for training beyond task level
- for improving visual realism
- for faithful force feedback
  (Non-authentic force-feedback may lead to the adoption of false impressions.)

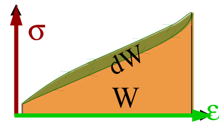
Accuracy vs. Computation time

Outline: Requirements for Soft Tissue Simulation

Physical Properties and Measurement Techniques



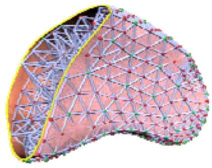
Physical Modeling and Material Laws



Mathematical Modeling

Displacement, Deformation

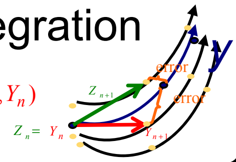
Spacial Discretisation



Some Current Simulators and the VirTis Simulator

Time Integration

$Y_{n+1} = Y_n + hf(t_n, Y_n)$



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Physical Properties and Measurement Techniques

Physical properties of Soft Tissue

Soft Tissue deformation is:

1. **elastic:** retreats to rest (spring)
2. **viscous**: damping

   but neither uniform nor immediately
3. **plastic**: non-reversible process

   tearing, cutting

Blood filled tissue is highly incompressible

Measurements in Biomechanics

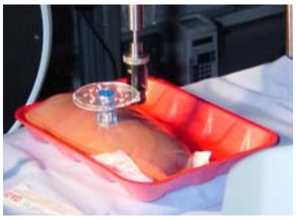
Tissue is Point of Interest in **Biomechanics**

Focusing on skin, vessels, muscles, bone and cells

“Standard” textbook: Fung, *Biomechanics: Mechanical properties of living tissue*

Most work up to mid 90s: Ex vivo

Now focussing: In vivo



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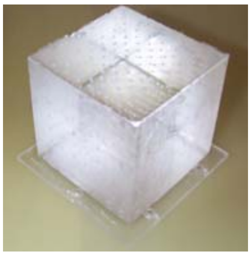
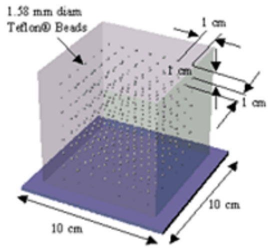
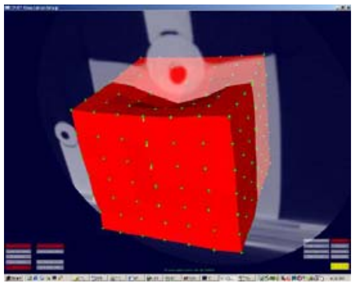
Current Activities

- Enhance database
- Define standard benchmarks:
  - www.truthcube.org,
  - Nava, Valtorta, Mazza (http://www.zfm.ethz.ch/e/biomechanics/)



- Comparative measurements [Ottensmeyer 2003]
- Develop better in vivo instruments

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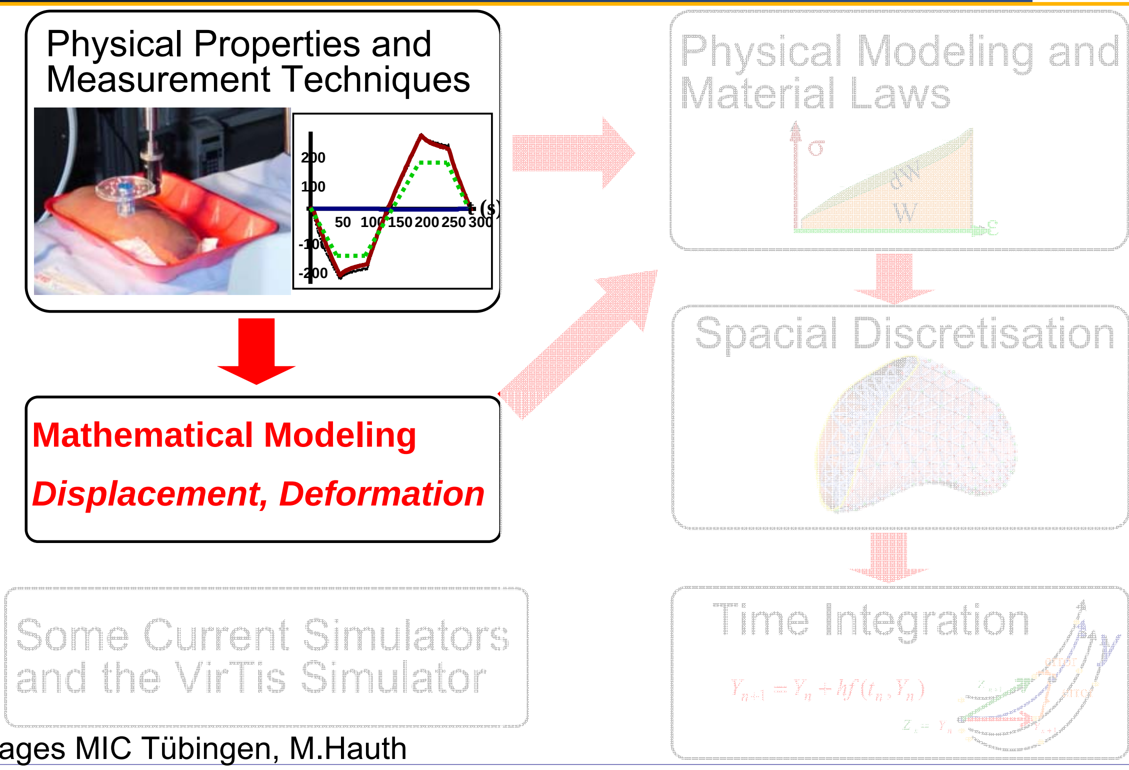
Mathematical Modeling



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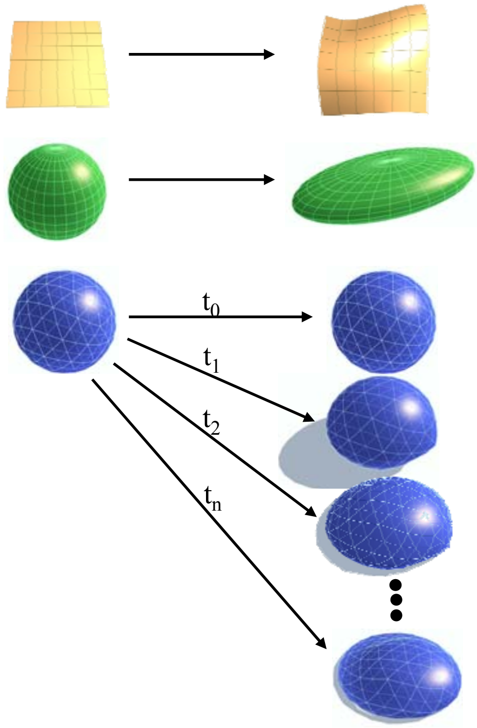
Mathematical Model

Parametrized Surface: $A: \mathbb{R}^2 \supset K \rightarrow \mathbb{R}^3$

Rigid Body: $S: \mathbb{R}^3 \supset K \rightarrow \mathbb{R}^3$

Deformable Solid: $\phi: \mathbb{R}^3 \supset K \times [0, \infty) \rightarrow \mathbb{R}^3$

Configuration ϕ



Often: initial configuration $K = \phi(\cdot\,, 0) = \mathrm{id}$

Displacement Field $\mathrm{u} := \phi - \mathrm{id}$

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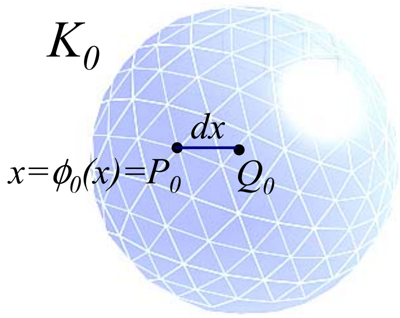
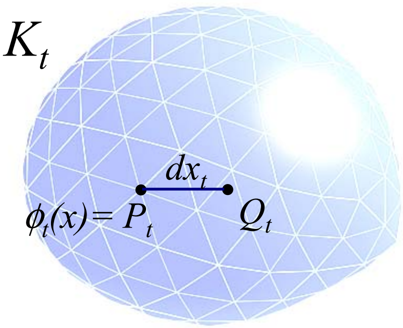
Measure of Deformation: Strain ε



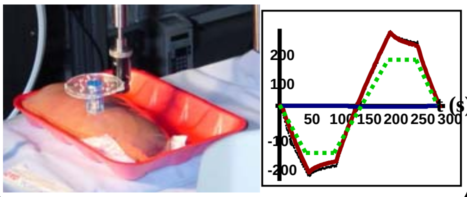


$$\Rightarrow \|dx_t\|^2 - \|dx\|^2 = \langle \nabla\phi_t dx, \nabla\phi_t dx \rangle - \langle dx, dx \rangle = \langle (\nabla\phi_t^T \nabla\phi_t - id) dx, dx \rangle$$

Define $\varepsilon := \tfrac{1}{2}(\nabla\phi_t^T \nabla\phi_t - id) = \tfrac{1}{2}(\nabla u_t^T + \nabla u_t + \nabla u_t^T \nabla u_t)$

Physical Modelling and Material Laws

Physical Properties and Measurement Techniques



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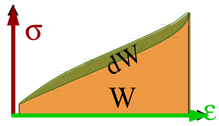

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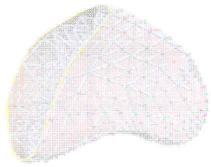
Displacement, Deformation

Spacial Discretisation



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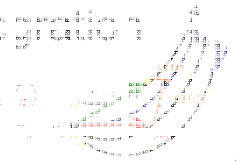
$Y_{n+1} = Y_n + hf(t_n, Y_n)$



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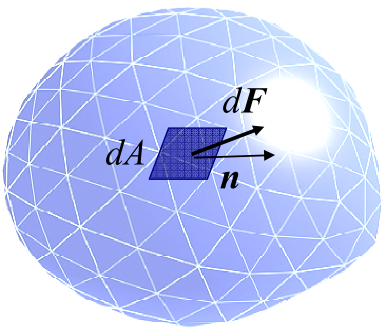
Material laws

strain tensor ε: geometrical state.

stress tensor σ: internal forces.



$$\frac{d\boldsymbol{F}}{dA} = \boldsymbol{\sigma} \cdot \boldsymbol{n}$$

Assumption: The stress σ is a function of strain (-history).

$$\sigma = \sigma(\varepsilon) = \sigma(\varepsilon(u))$$

Material law. linear or non-linear

Non-linear for large strain/displacement (*geometrical non-linearity*)

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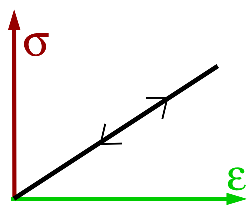
Blood filled tissue is highly incompressible

Material laws

Elastic, isotropic, homogeneous solid:

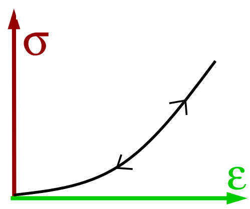
Hooke's Law $\sigma = C\varepsilon$



Nonlinear elastic solid:

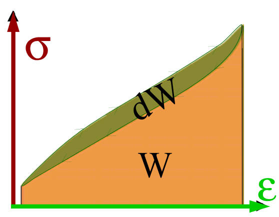
- Mooney-Rivlin
- Neo-Hooke
- Veronda-Westermann

$\sigma = f(\varepsilon)$



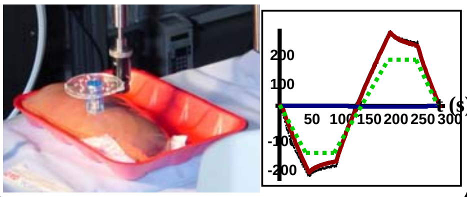
Visco-elastic solid:

$$\sigma(t) = \int_{-\infty}^{t} R(t-\tau)\,\dot{\varepsilon}(\tau)\,d\tau$$

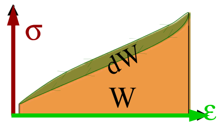


Spacial Discretisation

Physical Properties and Measurement Techniques



Physical Modeling and Material Laws



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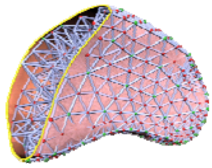

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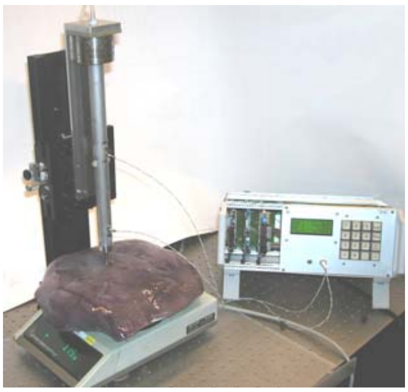
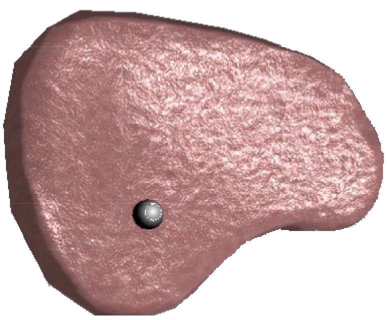
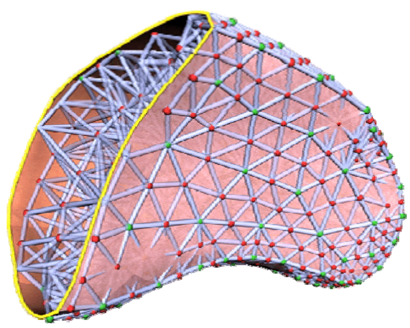
From Displacements to Simulation







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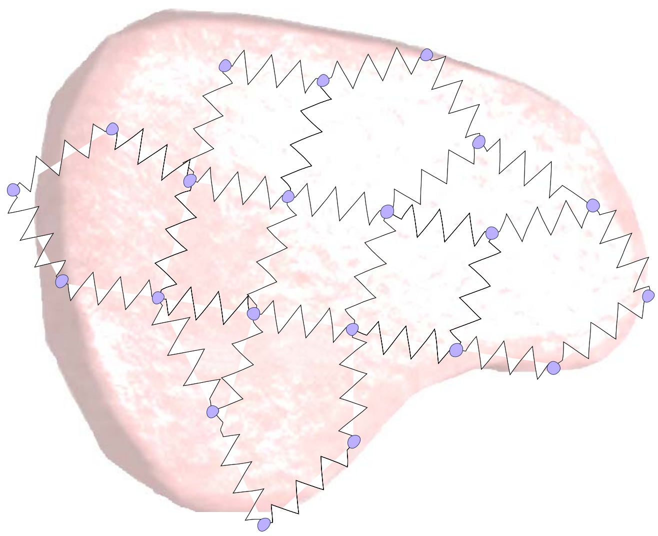
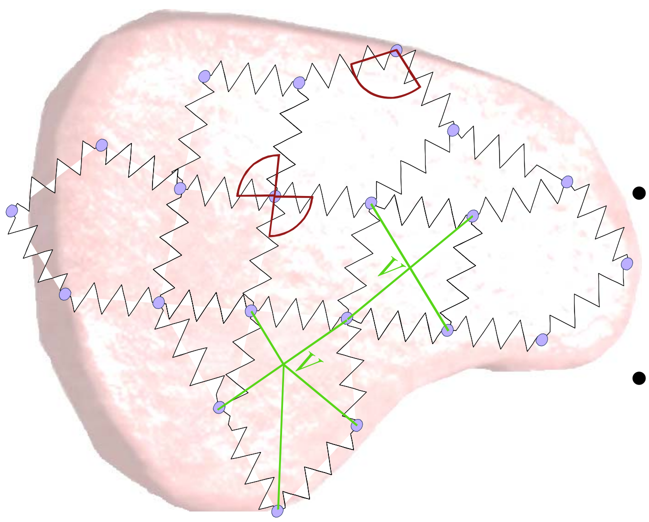
Mass-Spring/Damper Systems



- Arbitrary Topology
- Very difficult to fit to physical data (impossible?)
- Forces defined on edges (pairs)
- Can be over- or underdetermined

Generalized Particle System



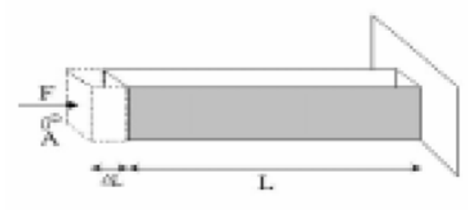
- Additional forces to fix shortcomings: Shear springs, Bend springs
- Additional non-spring forces, like volume preservation

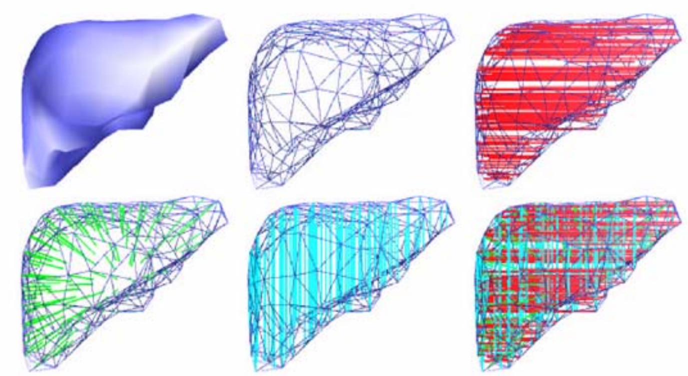
→ **Generalized Particle System**

(Forces between particles)

LEM/REM

- Physical simulation of a Long Bar filled with an incompressible fluid.
- Object decomposed into bar elements





[Balaniuk et al. 2000, 2001, 2002; Laugier et al. 2002]

Images taken from Balaniuk and Laugier

Finite Differences / Finite Element Method

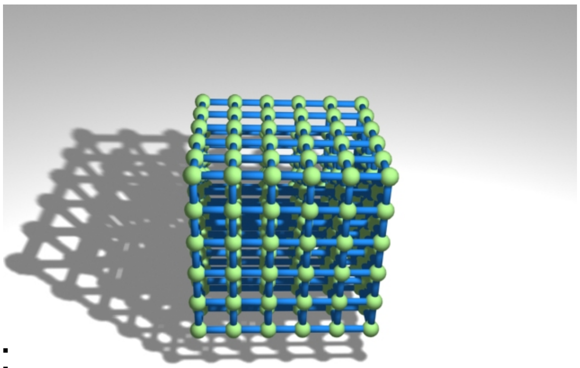
- Toolbox to cast a physical formulation into a simulation
- Sound derivation from continuum mechanics
- Standard method in engineering
- Computationally expensive

Finite Differences Method (FDM)

$\mathrm{div}\ \sigma - f = 0$ results in a PDE

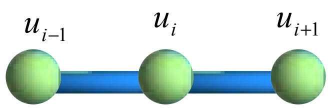
- u sampled on *regular* grid
- differential quotients

➡ difference quotients (stencils):



$$\frac{\partial u_i}{\partial x} = \frac{u_{i+1} - u_{i-1}}{x_{i+1} - x_{i-1}}$$

$$\frac{\partial^2 u_i}{\partial x^2} = \frac{u_{i+1} - 2u_i - u_{i-1}}{(x_{i+1} - x_{i-1})^2}$$



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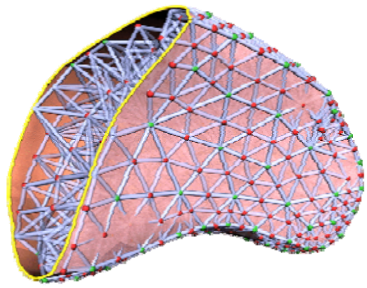
Finite Elements (FE)

Approximation with finite d.o.f., with basis φ_i („shape functions“)

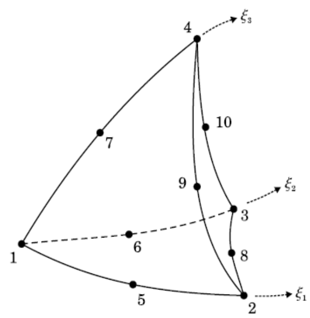
$$u \rightarrow \sum u_i \varphi_i$$



time dependent problem $\Rightarrow$ **ODE**

For example: *Linear* trivariate functions :

$$\vec{u}(\vec{\xi}) = \vec{\mu}_0(1 - \xi_1 - \xi_2 - \xi_3) + \vec{\mu}_1\xi_1 + \vec{\mu}_2\xi_2 + \vec{\mu}_3\xi_3$$



or higher order, e.g. quadratic
(more complicate!!)

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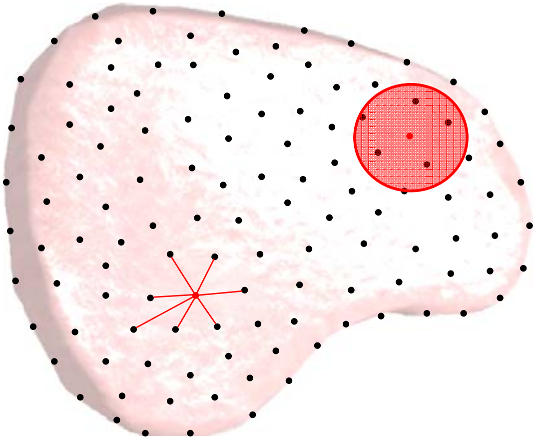
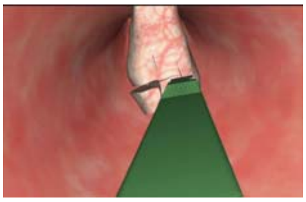
Mesh free methods





- Arbitrary Topology
- Support zone of each node
- Basis function

$$u \rightarrow \sum u_i \Phi_i$$

- Very good for tearing, cutting (no remeshing necessary)

- Not real time yet

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Methods

Speed

- Mass spring systems (2D/3D)
- Generalized Particle Systems
- Long Element Method
- Mesh free Method
- Finite Differences / Finite Elements

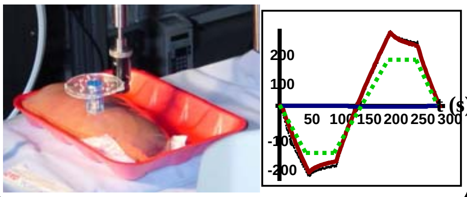
Physically reasonable

Accuracy

Accuracy vs. Computation time

Time Integration

Physical Properties and Measurement Techniques



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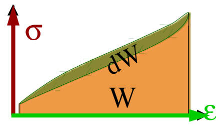

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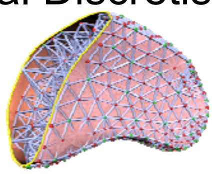

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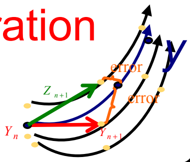

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Equations for deformable objects

Equation of equilibrium

$$\delta(E_{elast} + E_{ext}) = 0 \qquad \operatorname{div}\sigma - f = 0$$

No inertia and viscosity (dynamical effects)

➡ Equation of motion

$$\delta(E_{elast} + E_{kin} + E_{ext}) = 0 \qquad \operatorname{div}\sigma + f = \rho \frac{\mathrm{d}}{\mathrm{dt}} v$$

Discretize: Solve for time steps

Evaluating a Method

Criteria:

- Convergence — timestep →0
- Accuracy — u_{approx} - u
- Stability — solution →∞
- Efficiency

Numerical Integration

Abstract problem:

$$y' = f(t, y)$$

Goal:

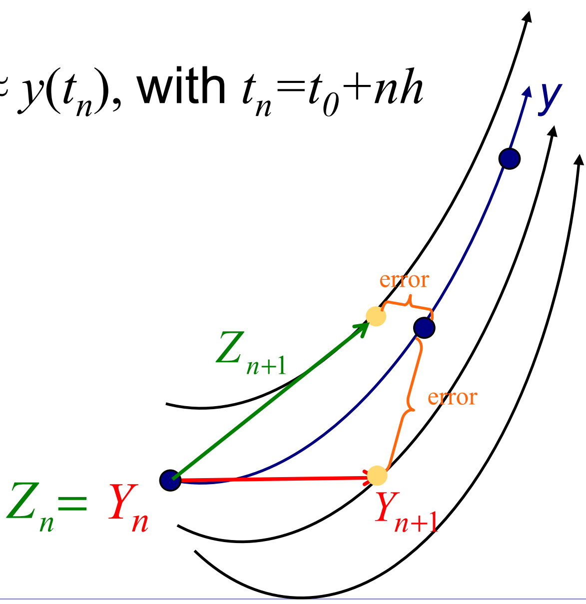
Find approximations $Y_n \approx y(t_n)$, with $t_n = t_0 + nh$

Explicit Euler

$$Y_{n+1} = Y_n + hf(t_n, Y_n)$$

Implicit Euler:

$$Z_{n+1} = Z_n + hf(t_{n+1}, Z_{n+1})$$



Summary: Integration Methods

Implicit methods:

↗ arbitrary large time steps

↘ need to solve large (non-)linear systems

Explicit methods:

↘ Have *strict* time step restrictions

↗ only need a few function evaluations

For **elastic equations**:

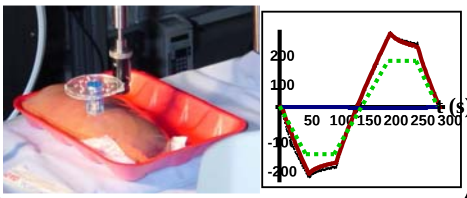
↗ Implicit methods are superior due to large time steps

But they are computationally expensive

↘ Because the Jacobian changes due to the nonlinearity

Current Simulators

Physical Properties and Measurement Techniques



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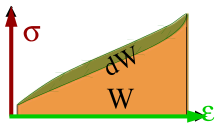

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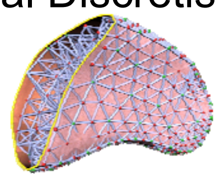

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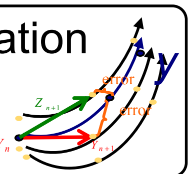

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Some Simulators

State of the art:

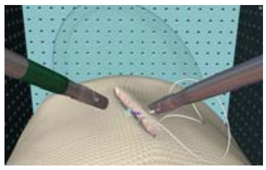
- Mentice, Simsurgery,
- Immersion, Select IT VEST (Kismet), Simbionix, Surgical Science, Xitact

Commercial

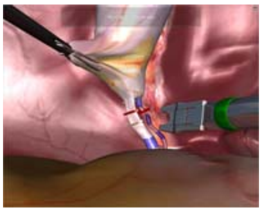
- INRIA Epidaure
- CoMe
- VirTis

Research

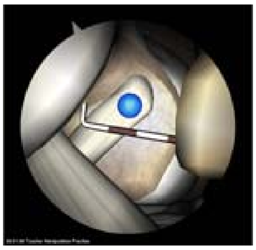
MIST VR by Mentice / Simsurgery



- Focuses on *basic* skills and tasks
- Studies show improved learning
- No force-feedback, thus comparably *cheap*



- Cholecystectomy



- Arthroscopy (shoulder, knee)

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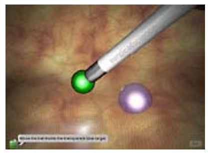
Commercial

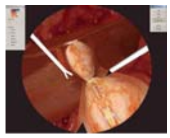
- Supposed to use Mass Spring and/or variations of LEM
- Include basic lessons
- Started with cholecystectomy modules
  now also cystoscopy, ureteroscopy, … (in prep. ear-nose-throat surgery)
- Force Feedback, stereoscopic view

- Immersion Medical (USA) (www.immersion.com) LapSim

- Select IT Vest Systems (Germany) (www.select-it.de) VS One





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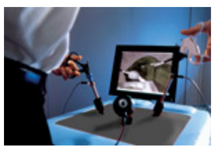
Simbionix (Israel) GI,LAP, URO; PERC Mentor
(www.simbionix.com)



Reachin Technologies (Sweden)
(www.reachin.se)

Surgical Science (Sweden)




XiTact (Switzerland) (www.xitact.com) LS 500

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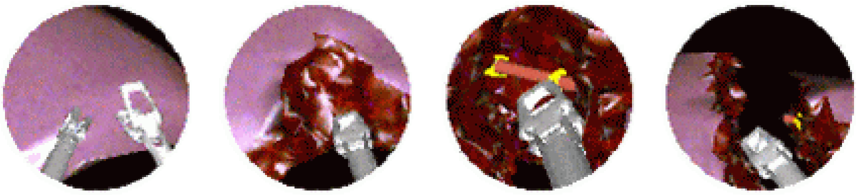
INRIA / Epidaure ->Asclepios

- 1992 - 31.10.2005 , includes tissue modelling as subproject

→ New project Ascelpios:Medical and Biological Image Analysis

- Finite elements and equivalent tensor mass model
- Anisotropic Hook law
- Force extrapolation for haptic loop



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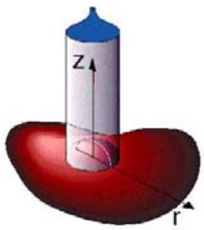
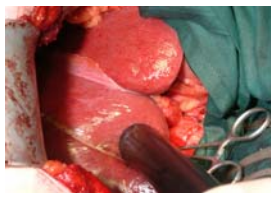
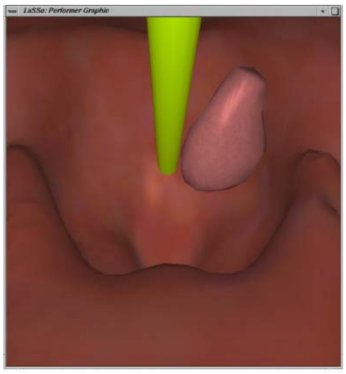
Lasso / CoMe (co-me.ch)

- Two large Swiss National projects
  - Lasso 1996-2000,
  - CoMe 1st phase 2001-2005, 2nd phase 2006 -)
- Soft tissue part focuses on hysteroscopy
- Includes measurement subproject
- FE, customized mass spring models, mesh free models
- Includes automated texture and pathology generation (e.g. fibroids),

  and special effects (e.g. bleeding (with CFD))







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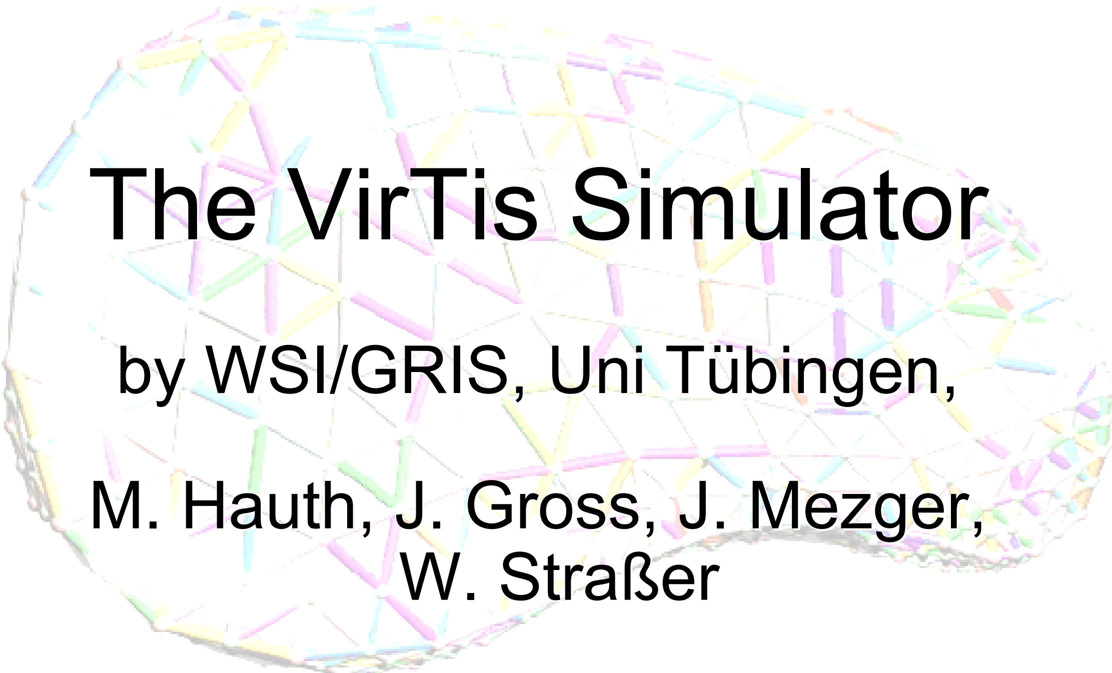
Summary

- Cheap basic simulators
- Current commercial simulators lack tissue fidelity
- In comparison to flight simulators, surgery simulators are in the 1930s (flight simulators were accepted in the mid 50s)
- Research simulators are maturing, using almost exclusively the finite element toolbox
- New promising branch: meshless methods



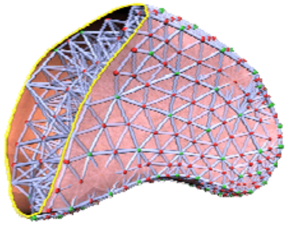
The VirTis Simulator

by WSI/GRIS, Uni Tübingen,

M. Hauth, J. Gross, J. Mezger, W. Straßer

Overview

- Tetrahedral finite elements with linear/quadratic shape functions
- Uses measured data as Prony series, different material laws, e.g. constQ
- Various Implicit or explicit time integration methods
- Haptic feedback with PHANToM



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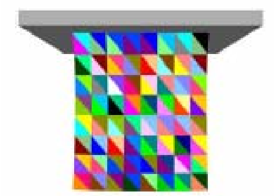
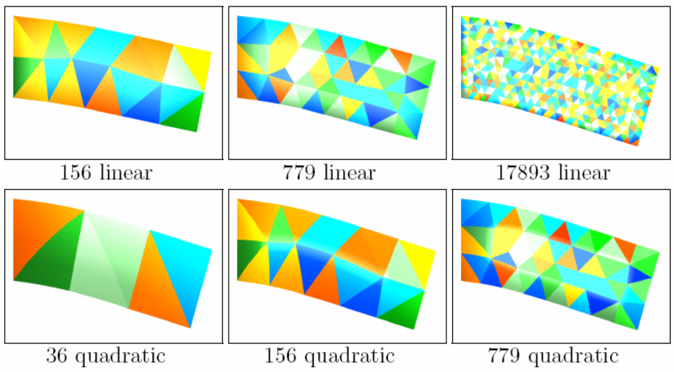
Demo Movies

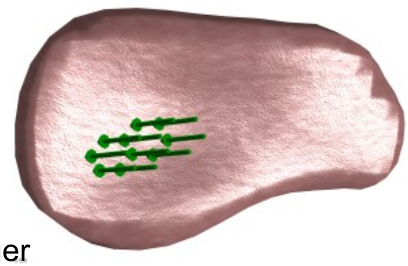
Spring-Model

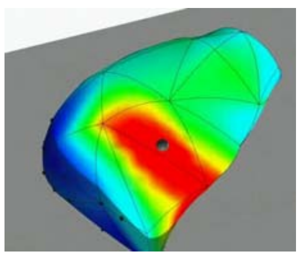
Visco-elastic-Model



Linear vs quadratic FE







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Summary: The VirTis Simulator

Provides real time finite elements with

- 5 memory parameters
- Real time (full Green strain tensor) :

~ 1000 linear elements
~ 100 quadratic elements } Athlon 64 3500+ (32 bit mode)

- Verification with gold standard (ABAQUS)

Theorie and Applications

Ph.D. Thesis Michael Hauth, Johannes Mezger
WSI/GRIS, university of Tübingen

Directions of further work

- Collision
- Tearing, Cutting, Suturing
- Adaptive Subdivision/Coarsening
- Hybrid models (FEM - mesh free)
- Numerical Methods (FEM, time integrators)
- Evaluation of haptic perception
- Parallelization
- …

Thank you

for your attention