Surgery simulation

Hervé Delingette

Epidaure Project

INRIA Sophia-Antipolis

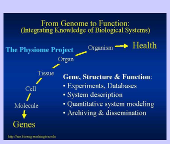
Virtual Human

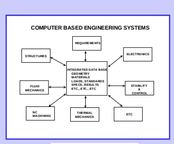
Development of computational models of the human body driven by :

- Better Understanding of biology and physiology at different scales
- New *in vivo image modalities* of the human body
- Fast Growth of computer technology and computer science

Global modeling of the human body

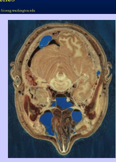
Physiome Project
International consortium



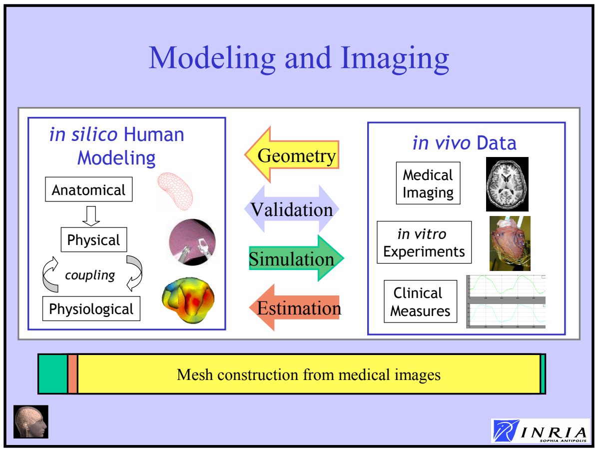


Digital Human
International consortium

Visible Human
NLM, USA



ESI Group
Virtual Dummies
for crash tests



Combining Images and Models

- **1st Goal**: Validation Quantitative Models
  - Reach a better understanding of human physiology and pathology by comparing measured and computed physical values
- **2nd Goal:** Assessment of physical parameters (diagnosis)
  - Guess physical parameters (pressure, speed, stress) by assuming that the physical behavior and boundary conditions are known
- **3rd Goal** : Prediction of physical behavior (therapy)
  - Predict anatomy based on the modeling of a physical phenomenon occurring during therapy (brain shift, cranofacial surgery)

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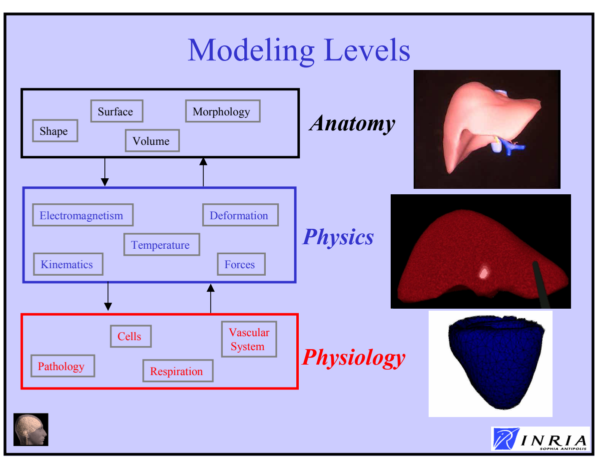
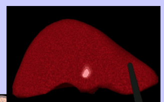
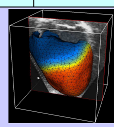
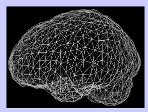


Overview of the talk

- 3 applications of human modeling

Application Type	Organ	Real/Time Constraint	Image Interaction	Physiological Modeling
Surgery Simulation	Liver	Yes	Validation	No
Diagnosis & Therapy Planning	Heart	No	Image Segmentation	Yes
Prediction of outcome	Brain	No	Validation	No

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Surgery Simulation

Acknowledgments:
- Clément Forest, Guillaume Picinbono, Stéphane Cotin, Jean-Christophe Lombardo, Nicholas Ayache
- INRIA projects member of the AISIM collaborative action (Imagis,Sharp,Macs)
- IRCAD

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Motivations of surgery simulation

- Increasing complexity of therapy and especially surgery
  - ➡ Increasing need for training surgeons and residents
- Medical malpractice has become socially and economically unacceptable
  - ➡ Increasing need for objective evaluation of surgeons (see Cordis Nitanol endovascular carotid stent)
- Natural extension of surgery planning

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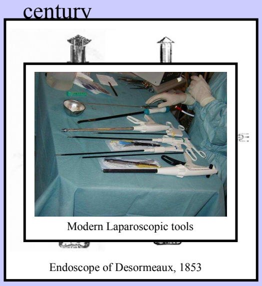
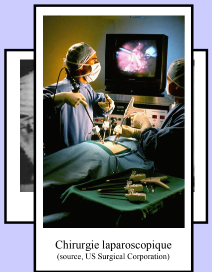
Simulation of laparoscopic surgery

- Laparoscopy originates from middle of XIXth century



Modern Laparoscopic tools

Endoscope of Desormeaux, 1853



Chirurgie laparoscopique
(source, US Surgical Corporation)

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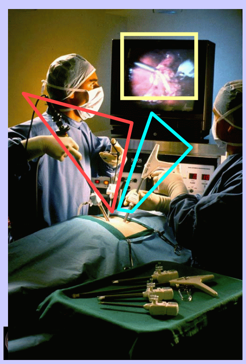
Need for Training



Hand-eye Synchronisation

Camera being manipulated by an assistant

Long instruments going through a fixed point in the abdomen

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Medical Robotics
Minimally Invasive Therapy

Zeus *(Computer Motion)*
Courtesy of L. Soler (IRCAD)

Da Vinci *(Intuitive Surgery)*
Courtesy of E. Coste-Manière (Chir)

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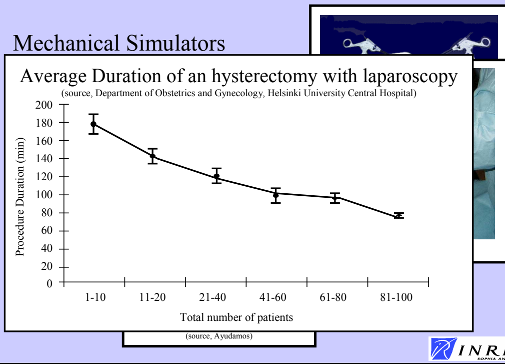
Current Training Techniques

- Mechanical Simulators

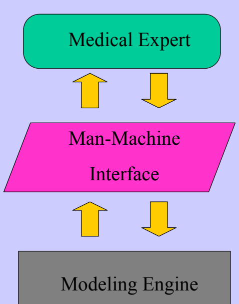


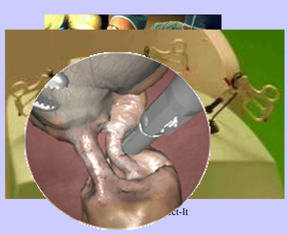
Training versus Rehearsal

- Training: Modelling a ***standard*** patient for teaching classical or rare situations

- Rehearsal: Modelling a ***specific*** patient to plan and rehearse a delicate intervention, and evaluate consequences beforehand

Description of a Simulator

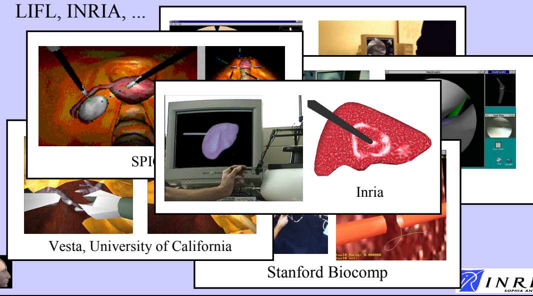




Source Surgical-Science

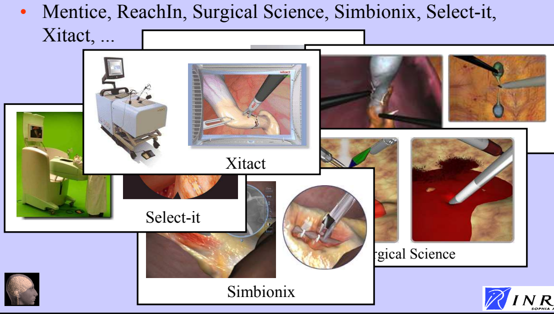
Simulators built at Universities

- Hull, Shefield, Stanford, Berkeley, Utrecht, ETZH, EPFL, LIFL, INRIA, ...



Simulators built by companies

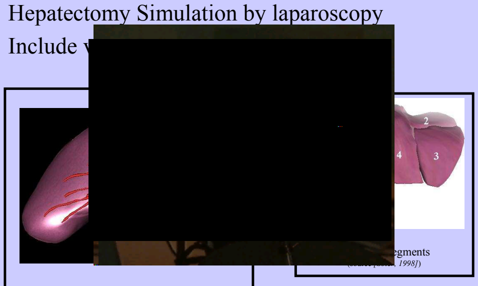
- Mentice, ReachIn, Surgical Science, Simbionix, Select-it, Xitact, ...



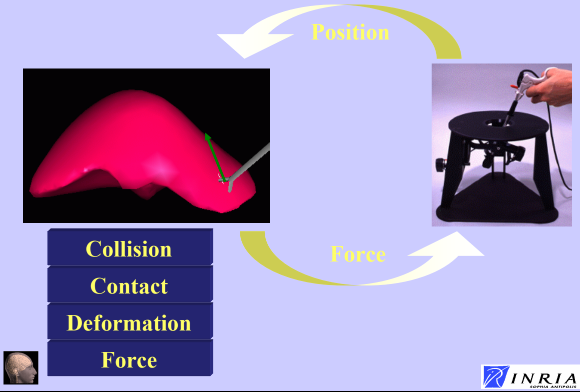
EPIDAURE SIMULATION

[Cotin, 1997] [Picinbono, 2001] [Forest 2003]

- Hepatectomy Simulation by laparoscopy
- Include [redacted]

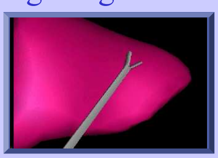


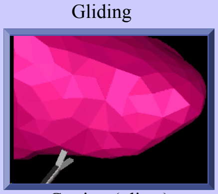
Simulator Workflow



Modeling basic surgical gesture

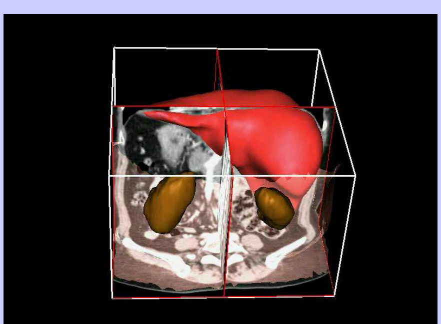

Gliding


Gripping


Cutting (pliers)


Cutting (US)

Complete Simulation



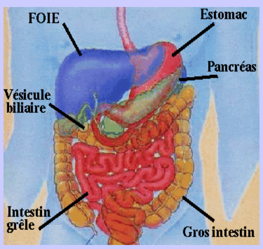
Different Technical Issues

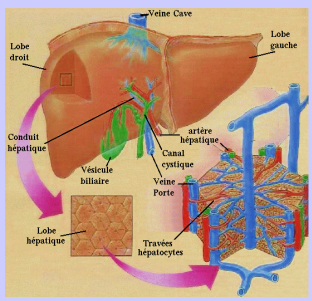
- Mesh Reconstruction from Images
- Soft Tissue Modeling
- Tissue Cutting
- Collision Detection
- Contact Modeling
- Surface Rendering
- Haptic Feedback

With real-time constraints

Hepatic Surgery

Hepatic Surgery Planning and Simulation

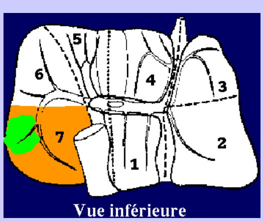


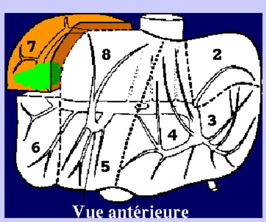


Surgical Context

Main Surgical Landmark :

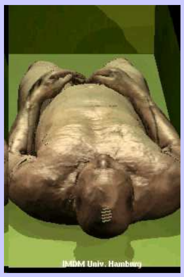
Liver Anatomical Segmentation

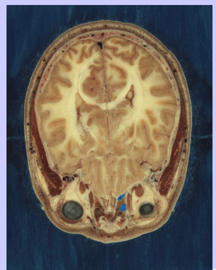




Visible Human

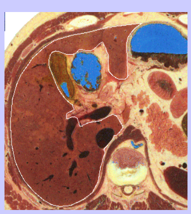
Joseph Paul Jernigan (died August 5th 1993)





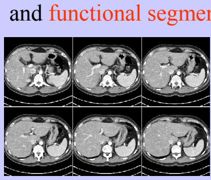
Liver Reconstruction

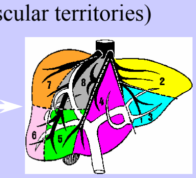
Deformation from a reference model reconstructed from the *« Visible Human Project »*



Specific Geometric Model

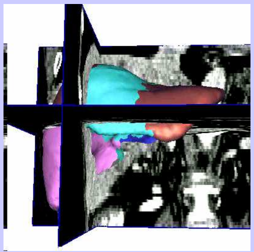
- Should correspond to the actual CT images of a given patient, and should provide external surface and functional segments (vascular territories)



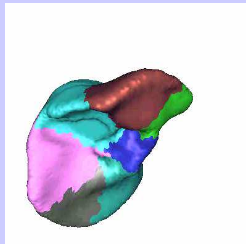


Liver Segmentation

CT scan image of the abdomen



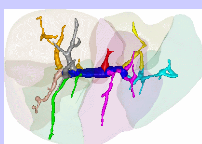
Time of convergence : 2 mn 12 s

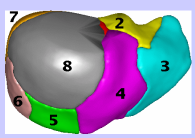


Extraction of Couinaud segments

Functional Segments

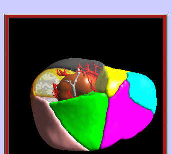
- Extraction of first branches of the portal vein
- Couinaud Segmentation defined by computing the influence zones (Voronoi) of the first branches of the portal vein.



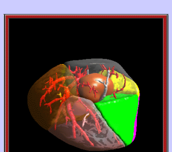


Planning with a geometric model

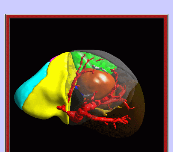
- Surgeon may plan his intervention by evaluating the relative position of lesions and Couinaud Segments.



Anterior View

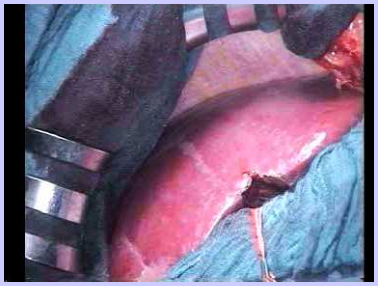


Right Lateral View



Postero-Superior View

Control of Planning with Augmented Reality



IRCAD

3D/2D non-rigid registration

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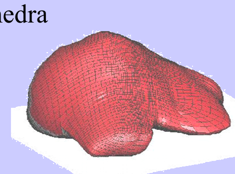
Volumetric Mesh Building

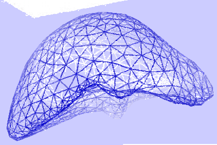
- Liver meshed with hexahedra

3 months work
(courtesy of ESI)



- Liver meshed with tetrahedra

  Automatically generated (10s with GHS3D Software)



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Different Technical Issues

- Mesh Reconstruction from Images
- Soft Tissue Modeling
- Tissue Cutting
- Collision Detection
- Contact Modeling
- Surface Rendering
- Haptic Feedback

With real-time constraints

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Specific Constraints

- Real-time constraints :
  - 25 Hz for visual feedback
  - 500 Hz for haptic feedback
- Boundary conditions posed in terms of specified displacements (essential BC)
  - Global Stiffness Matrix continuously updated
- Mesh Topology changes when simulating cutting

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Soft Tissue Modeling

- Proposed Models have 3 characteristics:
  - Using Volumetric Models
    Simulation of parenchymatous structures
  - Using Continuum Mechanics
    Simulation of linear and non-linear elastic materials
  - Using Finite Element Modeling
    Based on P_1 Linear Tetrahedron Element

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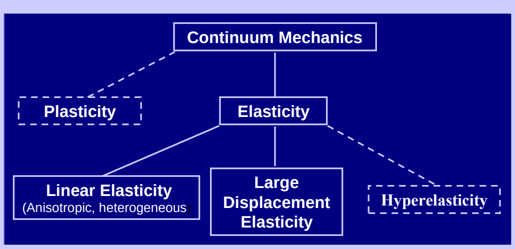
Continuum Mechanics



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Global Stifness Matrix

- Derivation of W yields a linear system of equations

$$F = [K]\, u$$

- with
  - [K] Rigidity Matrix (3n.3n)
  - u Displacement vectors (3n)
  - F External forces (3n) + boundary conditions

A Family of Models

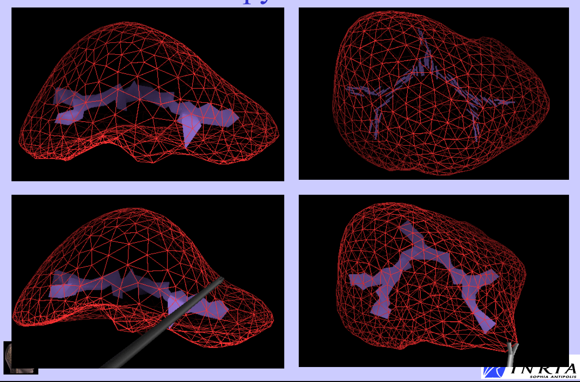
Pre-computed Linear Elastic Model / Non-Linear Elastic Model / Tensor-Mass Model

- Very fast / Topology Changes / Large displacements
- Small displacements / No topology changes / Limited to small displacements

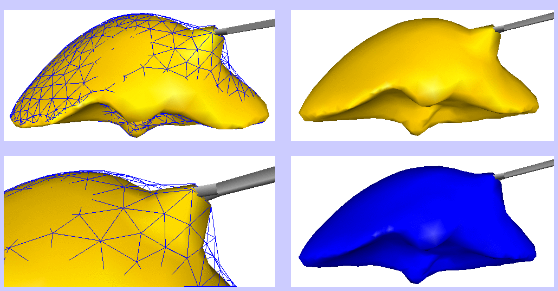
Soft Tissue Models

	Pre-computed Elastic Model	Tensor-Mass and Relaxation-based Model	Non-Linear Tensor-Mass Model
Computational Efficiency	+ + +	+	-
Cutting Simulation	-	++	++
Large Displacements	-	-	+

Anisotropy from vessels

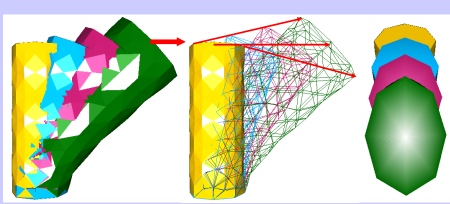


Anisotropy from the Glisson capsule

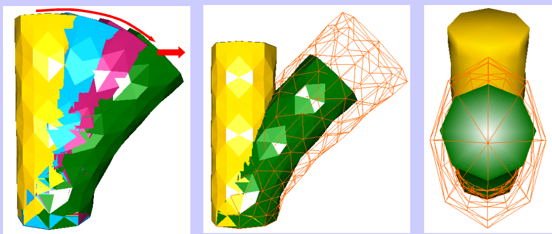


Shortcomings of linear elasticity

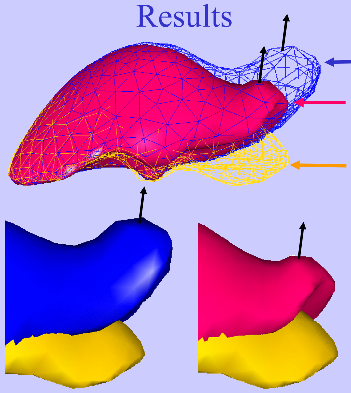
- Non valid for « large displacements»



Large Displacement Elasticity



Results



Incompressibility Constraints

- Biological Tissues are Incompressible
  - Hooke law: incompressible $\Leftrightarrow \lambda \rightarrow \infty$
  - Leads to instabilities
- Avoid flat tetrahedra at contact zones
- Add a penalty force linked to volume variation of each tetrahedron
  - Force proportional to volume variation
  - Oriented along the normal of the opposite triangle

$$\mathbf{F}_p^{incomp} = \alpha \, f\left(\frac{V - V_0}{V_0}\right) \mathbf{N}_p^{def}$$

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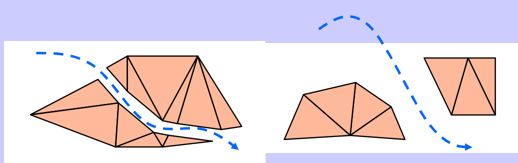
With real-time constraints

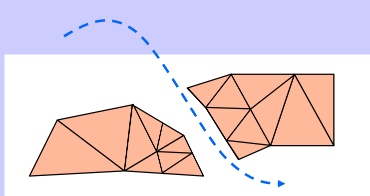
Different algorithms for cutting tetrahedral meshes

- Split of tetrahedra
  [Bielser, 2000] [Mohr, 2000] [Nienhuys, 2001]
  - + Accurate, realistic
  - - Decrease of Mesh Quality
- Removing Tetrahedra
  [Forest, 2002]
  - + Keeps a good mesh quality
  - - Gross cut

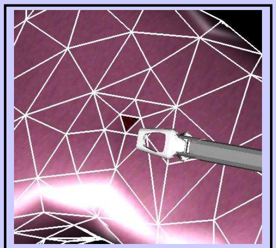


Proposed Technique

- Remove Tetrahedra
- Refine Mesh before removing material

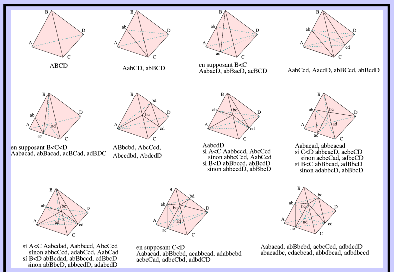


Dynamic Refinement



Example of refine-before-cutting

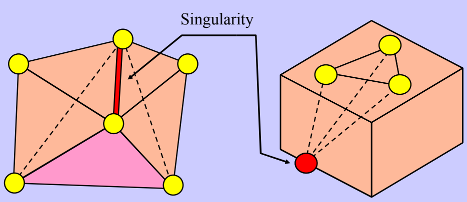
Refinement by Edge Split



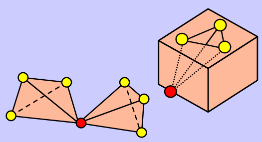
Decomposition of tetrahedra by edge split

Topological Singularities

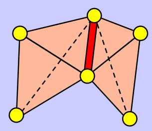
- Removing a tetrahedron may create a singularity (zero thickness at edge and vertices)



Definitions



- Several connected components of the neighborhood of a vertex



- Edge has more than 2 adjacent triangles on the surface

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Why Topological Singularities are a problem ?

- Need for a single unambiguous normal vector at each vertex :
  - Surface Rendering
  - Haptic Rendering
- Need for a simple neighborhood around each vertex
  - Neighborhood computation
  - Optimised data structure

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With real-time constraints

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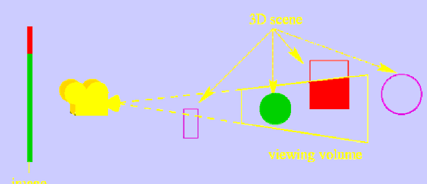
Previous Work

- A lot of research on Collision Detection

- Hierarchy of oriented bounding boxes:
  Gottshalk & al. - *Obb-tree: A hierarchical structure for rapid interference detection* - SIGGRAPH'96
- public domain package *RAPID*
- Very efficient,
  but needs pre-computation

The Rendering Process

- Camera = viewing volume + projection



- Two steps: geometry & rasterization

Collision Detection and Rendering analogy

a tool collides the organ

⇔

a part of the organ is inside the tool

⇔

if we define a camera with a viewing volume
that matches the tool geometry,
the organ will be in the picture.

Different Technical Issues

- Mesh Reconstruction from Images
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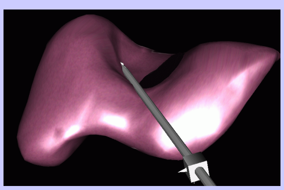
- Tissue Cutting
- Collision Detection
- Contact Modeling
- Surface Rendering
- Haptic Feedback

With real-time constraints

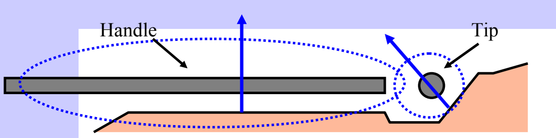
Tool-Soft Tissue Interaction

- Prevent penetration of tool inside the soft tissue
  - Detect intersections
  - Push explicitly mesh vertices outside the tool



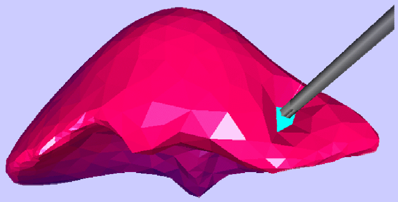
First Approach *[Picinbono, 2001]*

- 2 different tools : tip and handle
- Compute average normal in the neighborhood of the contact
- Projection of vertices in this plane



Collision Processing

- Contact with the tip of the instrument

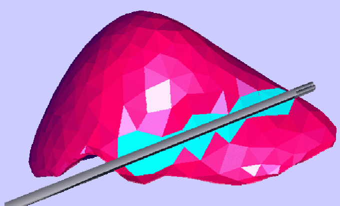


Projection on the plane defined by the tip of the instrument and the average normal of intersected triangles

INRIA

Collision Processing

- Contact with the handle of the tool

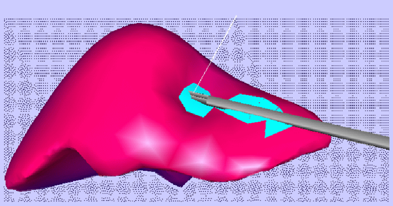


Projection on the plane defined by the tool direction and the averaged normal direction

INRIA

Collision Processing

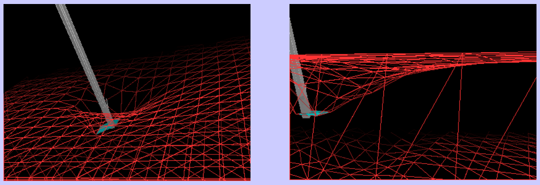
- Perform 2 detections simultaneously



INRIA

Possible interactions

- Slip on the surface

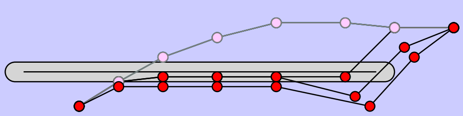


Limitations of this approach

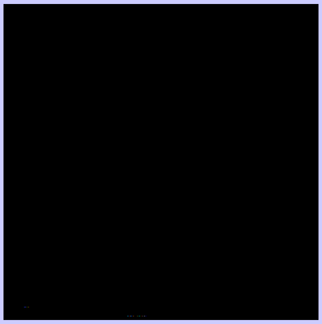
- Same normal vector for all triangles in the same neighborhood
- Leads to instabilities when handling a complex geometry

New approach

- Three steps
  - Prevent vertices to collide with the tool axis
  - Move vertices near the tip of the tool
  - Move vertices outside the volume of the tool



Example



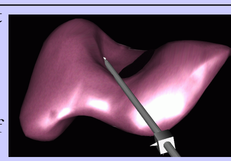
Different Technical Issues

- Mesh Reconstruction from Images
- Soft Tissue Modeling
- Tissue Cutting
- Collision Detection
- Contact Modeling
- Surface Rendering
- Haptic Feedback

With real-time constraints

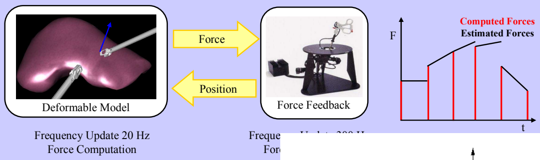
Haptic Feedback

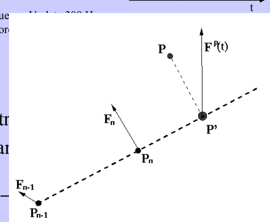
- Principle
  - Give a realistic sense of contact with the soft tissue
- Motivation
  - Increase realism
  - Naturally limit the amplitude of hand motion
- Pitfalls
  - Frequency update of haptics > 500 Hz
  - Frequency update of deformable models ≈ 30 Hz



Mouvement non contraint par le retour d'effort

First approach *[Picinbono, 2001]*

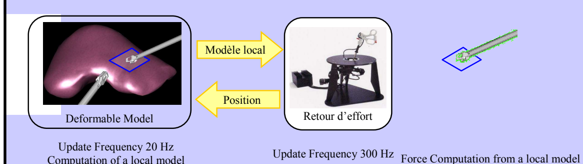




- Unstable if complex geometr
- Difficult extrapolation for lar

$$F^p(t) = F_n + \frac{\|P' - P_n\|}{\|P_n - P_{n-1}\|}(F_n -$$

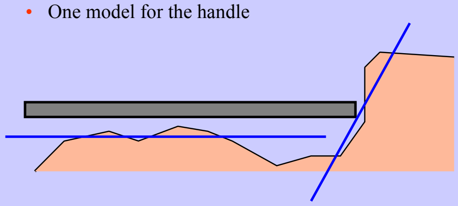
Local Model
[Mendoza, 2001] [Balaniuk, 1999] [Mark, 1996]



- Smooth Transition from one local model to the next

Computing the local model

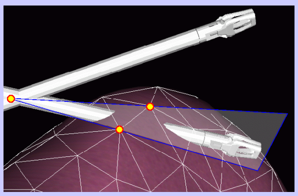
- Described as a set of planes
- One model for the tip
- One model for the handle



Force Computation

- Proportional to the penetration of the tool tip in the planes described by the local model

$$F = k.(EndP - O_P).\vec{n}_P$$



Limitations

- Sometimes difficult to compute local model
  - Stability issues
- Geometric Computation of forces
  - Realism