Surgical Planning and Biomechanical Analysis

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Overview

- CT
- Segmentation
- Surface Extraction
- Mechanical Model Generation
- Result Evaluation
- Analysis

Surgical Planning

MedEdit

FEA

Overview - CT

Overview - Surface Extraction

Marching Cubes ~800k triangles

Simplification ~100k triangles

Overview - Surgical Planning
Overview – Mechanical Model

CT

Segmentation
Surface Extraction
Mechanical Model Generation
Result Evaluation
Analysis
Surgical Planning
FEA

Overview – Result

CT

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CT

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Segmentation

- Convert 3D grayscale to 3D binary volume
- Algorithms
  - Threshold
  - Region Growing
  - Fuzzy Segmentation

Segmentation

Original slice
Segmented

Segmentation

Original image
Threshold value too low
Threshold value too high

Segmentation

Original image
Threshold value too low
Threshold value too high

Segmentation

Original slice
Segmented
Region Growing
- Joined regions
- Undetected regions

Fuzzy Connectivity
- The weakest link in the strongest path

Segmentation - Post Processing
- Remove possible noise
- Fill holes
- Morphological operations
  - Dilate
  - Erode
  - Opening
  - Closing

Surface Generation
1. Use the Segmented volume and create a triangle mesh of the surface
   - 2D
   - 3D
2. Simplify geometry

Contour following
- Collinear points are deleted
- Only the first and the last is kept
- Maximum distance as parameter of the simplification

Contour Simplification
Contour Simplification

2D contour reconstruction
- Bernhard Geiger (INRIA): NUAGES
- Input: a set of simple closed polygons on parallel planes
- Output: 3D surface

3D surface

Problems:
- 2D contours
- Pelvic bone is not “tubular”
- Horizontal resolution is low

Surface Generation

1. Use the Segmented volume and create a triangle mesh of the surface
   - 2D
   - 3D
2. Simplify geometry

Marching Squares I.
- Marching Squares (2D)
  - 16 configurations

Marching Cubes
- Fully 3D
  - 256 situations
  - Generalized in 15 families by rotations and symmetries
Marching Cubes II.

Marching Cubes
Surface generated with the marching cubes algorithm.
Number of triangles ~800,000

Surface Generation
1. Use the Segmented volume and create a triangle mesh of the surface
2. Simplify geometry
   - Reduce rendering time
   - Reduce analysis resources

Surface Simplification Methods
- Vertex Decimation
- Edge Collapse
- Vertex Clustering
- Face Merging

Vertex Decimation
- Schroeder et al, 92
- Based on controlled removal of vertices
- Loop
  - choose a removable vertex \( v \)
  - delete \( v \) and its incident faces
  - re-triangulate the hole
- Until
  - no more removable vertex exists or reduction rate fulfilled

Vertex Decimation
- Vertex is removable iff
  - Distance to average plane is lower than \( e_{\text{max}} \)
  - Distance to boundary is lower than \( e_{\max} \)
- Properties
  - Efficient
  - Simple implementation & use
  - Works on large meshes
  - Implemented in VTK
Edge Collapse

- Examine all vertex pairs
- Build queue of edges or $V_1, V_2$ pairs where $\|\vec{v}_1 - \vec{v}_2\| < t$

- Loop
  - Take edge $e$ from the queue with the least error
  - Delete $e$ and its triangles
  - Update queue

- Until
  - Queue is empty or target reduction reached

Vertex Clustering

- Object's bounding box is subdivided into a grid
- All vertices inside a cell are clustered to one representative vertex
- Layout of the grid controls the simplified model
- Properties
  - Very fast
  - Poor quality
  - No direct control of reduction rate

Co-planar face merging

- Kalvin, Taylor '96
- Partitions the surface into connected disjoint co-planar regions
- Regions are replaced by a polygon
- Polygon boundary is simplified
- Boundary retriangulated

Overview – Surgical Planning

- Repositioning
- Implants
Repositioning with the Mouse

Repositioning - Heptic device

http://www.sensable.com/index.htm

Surgical Planning

- Treat bone surfaces as objects in 3D space
- Transformations
  - Translation
  - Rotation
- Implants
  - Screw
  - Fixation Plate

Collision Detection

Surgical Planning

- 3D object positioning requires learning
- The model is 3D but the screen and the mouse is 2D
- Collision detection can help
- Automatic tool is needed

Repositioning using Registration

- Semi-automatic: user selects surface pairs
- Do registration on every pair one-by one
- Cost function: sum of distances to the nearest neighbours
- Search in 6 dim. space for the minimum of cost function
- EA optimization
Example

Properties

- With constraints: good matching of points
- Fast: 5-8 seconds
- BUT: possible errors
  - Segmentation
  - Simplification
  - User input
- Errors accumulate in complex cases

Complex Fracture

Male, 40Y, 7 fragments

Pairwise Surface Registration
Global Optimization

- All surface pairs are considered simultaneously
- Search space is \((n-1) \times 6\) dim.
- Stronger constraints
- Improves overall result

Global Positioning

- Model contains 12k points
- Points used for registration 2k-6k
- Slow

Global Positioning

- Repositioning
- Implants
  - Screws
  - Plates

Overview – Surgical Planning

- CT
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- Surgical Planning
  - Surface Model Generation
  - Result Evaluation
- Analysis

Original fracture
Female, 52Y, 6 fragments

Healthy bone mirrored and translated
Surgical Planning – Fixation Screw

- Screw parameters
  - Length
  - Insertion depth
  - Shank diameter
  - Tip length
  - Head length/diameter
  - Thread length
  - Major / minor diameters
  - Pitch

Surgical Planning – Fixation Plate

- Fixation plate
  - Width
  - Height
  - Length
  - Follow surface

Surgical Planning

Surgical Plan – Example II.

Finite Element Analysis

- History
- Basic concept
- Material properties
- Mesh, element library
- How an engineer works
Stress

- Stress is a measure of the internal distribution of force per unit area within a body that balances and reacts to the loads applied to it.

\[ F: \text{force}, \quad A: \text{crossectional area} \]

\[ \sigma = \frac{F}{A} \]

- Unit: N / m² = Pa

Strain

Strain is the geometrical expression of deformation caused by the action of stress

\[ \varepsilon = \frac{\Delta L}{L} \]

\( L \): original length
\( \Delta L \): change in length

Unit: no unit

Deformation

- Elastic region: the deformation is proportional to the force
- Plastic region: the material undergoes a non-reversible change

Hooke's law

- Hooke's law (1676): \( F \), is proportional to \( u \) by a constant factor, \( k \)

\[ F = ku \]

Where, \( k \) is the spring constant, \( u \) stretching distance

- Elastic materials: \( E \) is the elastic modulus.

\[ \sigma = E\varepsilon \]

Hooke's law

- Generalised to 3D by Cauchy

\[
\begin{bmatrix}
\sigma_{xx} \\
\sigma_{yy} \\
\sigma_{zz} \\
\sigma_{xy} \\
\sigma_{xz} \\
\sigma_{yz}
\end{bmatrix} =
\begin{bmatrix}
C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\
C_{12} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\
C_{13} & C_{23} & C_{33} & C_{34} & C_{35} & C_{36} \\
C_{14} & C_{24} & C_{34} & C_{44} & C_{45} & C_{46} \\
C_{15} & C_{25} & C_{35} & C_{45} & C_{55} & C_{56} \\
C_{16} & C_{26} & C_{36} & C_{46} & C_{56} & C_{66}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_{xx} \\
\varepsilon_{yy} \\
\varepsilon_{zz} \\
\varepsilon_{xy} \\
\varepsilon_{xz} \\
\varepsilon_{yz}
\end{bmatrix}
\]

Stress Stiffness matrix Strain

Hooke's law

- Izotropic material: the material properties are independent of direction (2 elastic constants)

\[
\begin{bmatrix}
P_x \\
P_y \\
P_z \\
P_{xy} \\
P_{xz} \\
P_{yz}
\end{bmatrix} =
\begin{bmatrix}
v & 0 & 0 & 0 & 0 & 0 \\
0 & 1-v & 0 & 0 & 0 & 0 \\
0 & 0 & 1-v & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
F_x \\
F_y \\
F_z \\
M_{xy} \\
M_{xz} \\
M_{yz}
\end{bmatrix}
\]

- Ortotropic material: 2-3 orthogonal planes of symmetry, where material properties are independent of direction within each plane

- Anisotropyc (21 elastic constants)
Young's modulus

• Modulus of elasticity
• The slope of the stress-strain curve
  \[ E = \frac{\sigma}{\varepsilon} \]
• SI unit: Pa

![Young's modulus diagram](image_url)

<table>
<thead>
<tr>
<th>Material</th>
<th>E (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond</td>
<td>1200</td>
</tr>
<tr>
<td>Steel</td>
<td>210</td>
</tr>
<tr>
<td>Iron</td>
<td>196</td>
</tr>
<tr>
<td>Aluminium</td>
<td>69</td>
</tr>
<tr>
<td>Bone</td>
<td>1.1</td>
</tr>
<tr>
<td>Cancellous bone</td>
<td>0.01</td>
</tr>
<tr>
<td>Rubber</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Poisson's ratio

• Defined as the ratio of the contraction strain normal to the applied load divided by the extension strain in the direction of the applied load
  \[ n = -\frac{\varepsilon_{\text{trans}}}{\varepsilon_{\text{longitud}}} \]
• \(-1 \leq n < 0.5\)

![Poisson's ratio diagram](image_url)

<table>
<thead>
<tr>
<th>Material</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber</td>
<td>0.495</td>
</tr>
<tr>
<td>Steel</td>
<td>0.28</td>
</tr>
<tr>
<td>Bone</td>
<td>0.3</td>
</tr>
<tr>
<td>Cork</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Negative Poisson's Ratio Materials

![Negative Poisson's Ratio Materials diagram](image_url)

Finite Element Method

• If we can not solve the original problem, let's brake it into smaller, but well known pieces and solve it that way!

\[ K = 2\pi r \]
\[ K_{ij} = n K_{ij} \]
\[ K_{ij} = K_{ij} = 2\pi \sin(\pi/n) \]
\[ \pi_{ij} = K_{ij}/2\pi = n \]

![Finite Element Method diagram](image_url)

Finite Element Mesh

• The model is a mesh of springs
  – **Nodes** define the geometry
  – **Elements** define which nodes are connected

![Finite Element Mesh diagram](image_url)
Element library I.
• Primitive elements
  - Rod element
  - Pipe element
  - Arbitrary profil

Element library II.
• Shell elements: 2D, but with thickness
  - Real
  - Triangle
  - Quadrangle

Element library III.
• 3D elements
  - Real
  - Tetrahedron
  - Hexahedron

How an engineer works
- Export design to a FEA system

How an engineer works
- Assign material property: Alloy Steel

How an engineer works
- Define fixed points
How an engineer works

Fixed points are marked green

Loader type, direction, and loaded area is defined

How an engineer works

Loaded area is marked with red arrows

Generation of the finite element mesh

How an engineer works

The finite element mesh
Irregular objects

- There is no CAD model of the patients broken bone
- **No automatic mesh generation**
- Fixed points and loaded areas

Mechanical Model Generation

- UI for Load and boundary conditions
- Direct mesh generation

Mechanical Model

- Geometrical model
  - Nodes
  - Finite elements (shell, tetra, hexa)
  - Material properties (Young’s modulus, Poisson’s ratio)
  - Load
  - Boundary conditions
  - Connections between objects

Load and boundary conditions

Load
Mechanical Model

Shell Elements

- Based on the geometry → 3-node shell el.
- Relation between objects → 2-node el.

Cortical bone is 100x stiffer

Mechanical Model Generation

- UI for Load and BC
- Mesh generation
  - Shell elements
  - Solid (tetra-, hexahedron) elements
    - Quadtree / Octree
    - Advancing Front
    - Delaunay

Octree/Quadtree

- Start with bounding box
- Recursively build quadtree

Mechanical Model Generation

- UI for Load and BC
- Mesh generation
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Octree/Quadtree

- Triangulate Intersection, Side, and Corner Points

Advancing Front

- Boundary is the initial front
- Process front segments
- Calculate ideal position for triangle
- Check radius around optimal node for existing front nodes

- Delete orig. front elements and insert new ones
  - Continue while front exists

- Delete orig. front elements and insert new ones
  - Continue while front exists

- Delete orig. front elements and insert new ones
  - Continue while front exists

- In case of multiple possibilities, chose best quality
Mechanical Model Generation

- UI for Load and BC
- Mesh generation
  - Shell elements
  - Solid (tetra-, hexahedron) elements
  - Quadtree / Octree
  - Advancing Front
  - Delaunay

Delaunay Triangle

- Delaunay Triangularization (DT): All triangles satisfy the empty circle property
- Empty circle property: No other vertex is contained within the circumcircle of any triangle

Bowyer-Watson algorithm

Iteratively insert new points:
1. Find all triangles whose circumcircle contains the new node.
2. Remove edges interior to these triangles
3. Connect nodes of this empty space to new node.

Lateral Compression
Example I. - Hip

Example II. - Pelvis
- Female, 50Y
- Monday:
  - Fall from a ladder
  - CT
- Tuesday:
  - Preparations
  - Surgical planning
- Wednesday
  - Operation
Example II. - Pelvis

Example III. - Pelvis

Example IV. - Jaw

Preoperative Plan

Biomechanical simulation

Conclusion

- Results match to the clinical expectations
- Quantitative comparative measurements still pending
- Possible Applications
  - Clinical practice
  - Education
  - Navigation
  - Research