Computer Simulation of Prostate Surgery

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Computer Simulation Virtual Training

Possibilities and advantages:

• Shorter training periods of time;
• Less risk for patients;
• Economic and exhaustive training;
• Visual and physical realism;
• Simulating bleeding, coagulation, optics, tissue texture, tissue resection, force reaction, among others;
• Critical cases in an controlled environment;
• Database of clinical cases;
• Simulating risk task and unexpected situations;
• Measuring and evaluating medical skills.
Transurethral Resection of the Prostate

Endoscopic view

Side view

Endoscopic view

- bladder
- verumontanum
- sphincter
- urethra
- prostate capsule
- rectum
- resectoscope sheath
- surgical electrode
- endoscope
- adenomatous prostate
- resectoscope sheath
- vaporisation roller
TURP Surgery Simulator Framework

Mechatronic Resectoscope

Virtual Prostate and Resectoscope
The Resectoscope

Tissue chips

Resectoscope

Resecting loop

Vaporization roller

capsule
cavity
adenoma
I) Disk-ring array and optical digital encoders for sensing rotational axes of the resectoscope;
II) Degrees of freedom, where a and b are linear, c, d and e are rotational;
III) Hall effect sensors array for controlling the Resecting loop.

The Mechatronic Interface

Schematic lateral view of the Interface with the prostate phantom
Linear model of the potentiometer for translational movements of the sheath.

Due to its simplicity this linear model was directly programmed as a routine of the microcontroller by doing linear interpolation.
The Mechatronic Interface Sensor Signals

Signals of each digital encoder for rotational movements of the sheath.

- Optical sensor give us three output signals: CH. A, CH. B and CH. I;
- Signal CH. I is useful only when the optical sensor gives a complete turn;
- Position and direction of rotation are determined by channels A and B.
Characterization of the Hall effect array for movements of the resecting loop.

- The Hall effect model was obtained at off-line stage by a fate-table that corresponds to the non-linear curve.
- The fate-table resolution is 0.5 mm.
- Finer displacements behind 0.5mm are calculated in real-time by linear interpolation of values in the fate-table.
The Signal Acquisition System

Microcontrollers embedded system

- Four PIC’s 16F876A for digital signals (3 for monitoring optical sensors, 1 for multiplexing data);
- LP3500 as master card and for analog signals (hall effect sensors and linear potentiometer).

Monitoring at 23 Hz
Virtual objects

- **Prostate** is modelled as a volumetric 3D mesh (tetrahedra);
- **Resectoscope** is modelled as a surface 3D mesh (triangles).
- **Collisions and interactions** are detected over the object surfaces (surface triangles);
- **Deformations and tissue cuttings** are modelled as a solid (volume tetrahedra).
Transurethral ultrasound images automatically annotated by a Point Distribution Model adjusted by a Genetic Algorithm (Arambula)
3D Model Reconstruction

1. Surface Sampling
2. Surface Interpolation
3. Volume Sampling
4. Mesh generation
5. Prostate mesh
Collision Detection

- At each recursion a Bounding-Box that covers the leaf spheres is computed;
- Spheres are divided through the orthogonal plane placed at the middle of the Principal Component of the box.

Collision Detection Algorithm

- $O(n \log n)$ for detection;
- $O(\log n)$ for simple mesh updating (triangle adding and removing);

<table>
<thead>
<tr>
<th>Prostate</th>
<th>Triangles</th>
<th>Response rate/s</th>
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<tbody>
<tr>
<td>1</td>
<td>2816</td>
<td>63.35</td>
</tr>
<tr>
<td>2</td>
<td>3128</td>
<td>63.15</td>
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<tr>
<td>3</td>
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<td>4</td>
<td>5292</td>
<td>52.48</td>
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<tr>
<td>5</td>
<td>5670</td>
<td>55.28</td>
</tr>
</tbody>
</table>

Stops after critical time (300 Hz)
Deformable Model and Collision Response

- After a collision is detected the soft tissue must deform slightly;

- Mass-spring method for deformable behaviour:

  \[ m_i \frac{d^2 x_i}{dt^2} + \gamma_i \frac{dx_i}{dt} + g_i(t, x_i) = f_i(t, x_i) \]

  - \( m_i \) - mass of the node \( N_i \);
  - \( x_i \) - coordinates of \( N_i \);
  - \( \gamma_i \) - damping coefficient of \( N_i \);
  - \( g_i \) - internal elastic force over \( N_i \);
  - \( f_i \) - external forces over \( N_i \);

- Deformations result from the reacting forces (by a penalty-based method depending of the penetration):

  \[ f = (\lambda V + \gamma \dot{V}) \hat{k} \]

  - \( \lambda \) - Stiffness
  - \( \gamma \) - Damping
  - \( V \) - Penetration
  - \( \hat{k} \) - Direction of contact

- Penetration field is computed from the collision history;
- Signed Distance Field as measure of penetration.

- \( O(\log n) \) for updating the sphere-tree after deforming (\( \log n \) is the height of the tree).
Tissue Deformation
Tissue Cutting for Vaporization

First prototype for Vaporization (tissue cutting by mesh erosion) ! Unrealistic! (Without mesh-refinement)
Deleting and Adding triangles

- Tissue resection is done without local mesh refinement;

- Removing triangles from surface mesh and adding the inner triangles exposed by the cut (around resecting radius);

- **Deleting triangles** to the tree consists on:
  a) removing the leaf and its parent and linking its brother to its grandparent;
  b) recursive bottom-up updating the sphere geometry of the ancestors of the triangle removed

- **Adding a triangle** simply consists on:
  a) creating a new leaf and inserting operation on binary trees at the lowest level (searching criteria is the principal component of object at each recursion);
  b) updating again the sphere-tree geometry

Adding and deleting a triangle from the mesh also takes $O(\log n)$
Interaction with Mechatronic Interface
Adaptive 3D Reconstruction

Adaptive Meshes modulated by Distance Field $D[\partial A]$

1. Segmentation
2. Interpolation
3. Adaptive Sampling (Monte Carlo)
4. Delaunay Tetrahedrization
5. Vertex Relaxation

Tetrahedral 3D Mesh

Surface 3D Mesh for Surface

Density ($mesh(\partial A)) \propto D[\partial A]$
System Architecture for Real “Real-time”

¿ Haptics ?

¿ Response ?

Sensors

Data Structures, Collision and Reacting forces

Deformation

\[ m \frac{d^2 x_1}{dt^2} + \gamma \frac{d x_1}{dt} + g_i(t, x_1) = f_i(t, x_1) \]

on CPU 65 Hz on, GPU at least 250 Hz

Texturing, Shading and Rendering

on CPU 65 Hz, on GPU at least 300 Hz

Virtual World

Movements 20 Hz, at least 40 Hz

¡ [20,30] Hz !

[Image]
The current state of the development of a virtual resectoscope interface for TURP surgery simulation system was presented; The aim is removing small volumetric tissue chips (not only considers the urethra surface); The device reproduce the five main movements of a real resectoscope; Measurements are monitoring in real-time at 23Hz with the Microcontrollers embebed system; Metrological evaluation (ZEISS MC850 Coordinates Measuring Machine, μm accuracy, 96% confidence) reveals an acceptable statistical error of 2.14 mm when the resecting head is located below 7 cm from the reference point. Increases drastically (7mm) for greater distances; Response rate of the collisions algorithm is 50 to 60 Hz (enough for real-time interactions); We are currently modelling tissue resection by mesh refinement.
Thank you!