Journal Club
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Dynamic Guidance for Robotic Surgery Using Image-Constrained Biomechanical Model

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MICCAI 2010
Paper Selection

- Overlapping interest in image guidance for robotic surgery
  

  - Real-Time Stereo Reconstruction in Robotically Assisted Minimally Invasive Surgery. MICCAI 2010
Background

• Primary clinical target: Vessel identification and harvest prior to totally endoscopic coronary artery bypass (TECAB), but also applicable to image-guided liver resection and partial nephrectomy, in the presence of respiratory motion

• Spatiotemporal registration:
  – Surface texture
  – Segmented mesh
  – Volumetrically rendered overlay regimes.
Methods

- **Stereo Feature Tracking** with combination of landmarks (max stable extremal regions) and traditional gradient-based image features

- **Spatiotemporal Registration** – least squares distance optimisation problem over projected 3D fiducial positions segmented from scan data and corresponding points recovered from the stereo video sequence.

\[
\sum_{i,j} \left[ \| p^L(Rs_i(\tau_j + \lambda)) - t^L(\tau_j) \|^2 + \| p^R(Rs_i(\tau_j + \lambda)) - t^R(\tau_j) \|^2 \right]
\]
Methods

- **Finite Element Simulation** – A total Lagrangian explicit dynamics algorithm implemented in GPU is used to model deformation of the heart resulting from surface positional constraints and the internal forces implied by the original 4D scan motion.

\[
M^t \ddot{U} + C^t \dot{U} + _0^t F = _0^t R
\]

M = constant lump mass matrix \hspace{1cm} C = damping matrix

\[t\dot{U} = velocity\]

\[t\ddot{U} = acceleration\]

\[^{t}F = nodal reaction force to element stresses\]

\[^{t}R = nodal reaction force to externally applied forces\]
Figure 4. Extension and compression of a cylinder.
Methods

• High-resolution meshes segmented and built from the original CT scan data

• Once spatial & temporal registered, tracked features are associated with interpolated mesh node positions at the corresponding point in time.

• Secondly, volumetrically rendered scan data is deformed by slicing each tetrahedral element individually, from back to front in planes perpendicular to the z-axis and alpha-compositing.

• Overlays are presented using the Inverse Realism technique described by Lerotic et al.
Results

- Phantom – Chamberlain Group Coronary Artery Bypass Graft (CABG) beating heart phantom.
  - Scanned at 90 bpm with a Philips 64-slice CT scanner, producing 20 uniformly spaced phases.
  - Outer fiducial markers manually segmented.
Results

The results shown on the left of Table 1 correspond to the surface-only, force-only (i.e. volume) and combined constraint modes. Averagely determined surface errors of 0.4712 mm and 0.4667 mm, respectively. The output frames in Figure 1 of the phases in order to recover the sequence. The results are compared over multiple cardiac cycles against the spatial locations of corresponding left and right 2D stereo locations of five such fiducials in the cadaveric specimen. In the first instance, the phantom was scanned at 90 bpm with a Philips 64-slice CT scanner, producing 20 uniformly spaced phases. Fiducial markers were conducted using a Chamberlain Group CABG beating heart phantom.

In order to assess 2D overlay accuracy when positional surface constraints are applied for simulations where surface constraints and internal forces are applied respectively determined surface error of 0.4712 mm and 0.4667 mm according to the maximum errors, and root-mean-square deviations are determined over section 2.2 had average left and right 2D stereo locations of five such fiducials.

The results are compared over multiple cardiac cycles against the spatial locations of corresponding left and right 2D stereo locations of five such fiducials in the cadaveric specimen. In the first instance, the phantom was scanned at 90 bpm with a Philips 64-slice CT scanner, producing 20 uniformly spaced phases. Fiducial markers were conducted using a Chamberlain Group CABG beating heart phantom.

For quantitative assessment of the proposed method, detailed phantom experiments were conducted using a Chamberlain Group CABG beating heart phantom.
Results

Table 1. Projected surface texture and internal structure overlay errors

<table>
<thead>
<tr>
<th>error (mm)</th>
<th>surface overlay</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>surface</td>
<td>volume</td>
<td>combined</td>
</tr>
<tr>
<td>average</td>
<td>0.33</td>
<td>0.69</td>
<td>0.36</td>
</tr>
<tr>
<td>maximum</td>
<td>0.64</td>
<td>1.40</td>
<td>0.68</td>
</tr>
<tr>
<td>RMSD</td>
<td>0.36</td>
<td>0.80</td>
<td>0.40</td>
</tr>
</tbody>
</table>

- Surface overlay – Compare 2D accuracies against a typical feature manually tracked in the left video stream
  - Surface (- -)
  - Volume (force --)
  - Combined (-)
- Surface most accurate, but combined degrades marginally
Results

Table 1. Projected surface texture and internal structure overlay errors

<table>
<thead>
<tr>
<th></th>
<th>Surface</th>
<th>Volume</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>fiducial #1</td>
<td>0.23</td>
<td>0.23</td>
<td>0.23</td>
</tr>
<tr>
<td>fiducial #2</td>
<td>0.25</td>
<td>0.30</td>
<td>0.31</td>
</tr>
<tr>
<td>fiducial #3</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>fiducial #4</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>fiducial #5</td>
<td>0.33</td>
<td>0.16</td>
<td>0.18</td>
</tr>
</tbody>
</table>

- Internal overlay – Compare 3D CT features against barycentric interpolation of point in FEM mesh
  - Surface (- -)
  - Volume (force --)
  - Combined (-)

- Volume most accurate, but combined degrades marginally
Conclusion

• Combined constraint mode offers a good compromise over the surface-only and internal force-only alternatives.

• New modeling framework for fusing preoperative tomographic and intraoperative endoscopic data in a dynamic environment, such that accurate overlays can be rendered in both surface texture and internal structure regimes.

• A physically-based, inverse finite element simulation transforms preoperative motion into a representation where it can be readily combined with tissue surface constraints.