Minimally Invasive Retrieval of Foreign Bodies from a Beating Heart under 3D Ultrasound Guidance

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Foreign Bodies in the Heart

- **Causes**
  - Thrombi after myocardial infarction
  - Explosions, gunshot injuries
  - Emboli from extremities

- **Symptoms**
  - Cardiac tamponade
  - Hemorrhage
  - Shock
  - Infection
  - Embolism
  - Arrhythmia
  - Valve dysfunction

(Actis Dato, 2003)
Standard Surgical Workflow

1. Stabilize patient with a chest tube
2. Stop heart with cardiopulmonary bypass
3. Detect foreign body in images
   - X-ray imaging
   - Ultrasound imaging
4. Incise skin through midline
5. Open chest bone
6. Open pericardiac sac
7. Open myocardium (heart muscle)
8. Remove foreign body with pincers or finger
9. Repair myocardium using patches
10. Close sternum using staples

Technique established during WW2 by US Army surgeons
Literature


Minimally Invasive Interventional System

- Workstation Computer
- Philips 3D Ultrasound
- Cone Beam CT (optional)
- US Beacon (on tip)
- Thrombus
- Combined RCM Robot and Dexterous Manipulator
- 3D TEE Probe
- TEE
Related Work

• 3D TTE to robotically guide surgical tool towards static targets in a water tank (Novotny, Stoll, Dupont, Howe, 2007)
• 3D ultrasound to robotically guide needle towards static target in tissue phantom (Liang, Allmen, Rogers, Light, Smith, 2010)
• Heartbeat-compensated surgical device (1 degree-of-freedom) designed using heart motion parameters extracted from 3D video (Yuen, Kettler, Novotny, Plowes, Howe, 2009)
• Enhanced visualization of ferrous shrapnel under 3D ultrasound using variable magnetic field (Rogers, Light, Smith, 2009)
• 3D ultrasound to robotically guide needle towards static target in tissue phantom (Liang, Allmen, Rogers, Light, Smith, 2010)

• “Current 3D US systems are prohibitively expensive, suffer from low voxel resolution, and most importantly, they do not provide each access to real-time volumetric data stream to the user” (Krupa, Fichtinger, Hager, 2009)
Characterizing Fragment Motion

Beating Heart Phantom Ultrasound (TEE) Video

20 s @ 20 fps

(MICCAI 2011)

Foreign Body Trajectories from NCC and Manual Tracking

<table>
<thead>
<tr>
<th>Tracking (Mod. 3D NCC)</th>
<th>Motion Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS Error</td>
<td>2.3 mm</td>
</tr>
<tr>
<td>Range</td>
<td>40.2 mm</td>
</tr>
<tr>
<td>Speed</td>
<td>343.5 mm/s</td>
</tr>
<tr>
<td>Acceleration</td>
<td>7800.0 mm/s²</td>
</tr>
</tbody>
</table>

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Robotic Retrieval, Take 1

- Speed mismatch:
  - Fragment: 343.5 mm/s
  - Robot: 20 mm/s
- Reduce speed by 9x → 2.1 mm error RMS
- Propose alternate retrieval strategies

(Biorob 2012)
Minimally Invasive Retrieval

Direct pursuit (chasing)
Minimally Invasive Retrieval

Direct pursuit (chasing)  Indirect pursuit (ambushing)
Minimally Invasive Retrieval

Direct pursuit (chasing)

- Requires a very fast robot
- Additional safety concerns

Indirect pursuit (ambushing)

Advantage: Slower robot can be used
Experimental Setup

- Replica of human heart
- Pneumatic pistons pump water in/out of phantom
- Heartbeats programmed via servo controllers
Experimental Setup

- Recorded 5 sets of 3D ultrasound images (20 s @20 fps)
Candidate Capture Locations

- **Most Occupied**: Spatial probability of fragment location
Candidate Capture Locations

• **Most Occupied**: Spatial probability of fragment location

• **Most Dwelled**: How long does the fragment dwell in a location?
  – How long until it comes back again?
Candidate Capture Locations

• **Most Occupied:** Spatial probability of fragment location

• **Most Dwelled:** How long does the fragment dwell in a location?
  – How long until it comes back again?

• **Most Frequentened:** How often does it traverse a location?
Candidate Capture Locations

- **Most Occupied**: Spatial probability of fragment location
- **Most Dwelled**: How long does the fragment dwell in a location?
  - How long until it comes back again?
- **Most Frequented**: How often does it traverse a location?

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Dataset A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>Min</th>
<th>Mean</th>
<th>Max</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Most Occupied Location</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>%Time Occupied</td>
<td>39.8</td>
<td>38.0</td>
<td>57.5</td>
<td>54.0</td>
<td>63.0</td>
<td>38.0</td>
<td>50.5</td>
<td>63.0</td>
<td>11.1</td>
</tr>
<tr>
<td><strong>Most Dwelled Location (seconds)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t_{dwell}$ Avg. (Max)</td>
<td>0.33 (0.70)</td>
<td>0.54 (0.75)</td>
<td>2.00 (5.90)</td>
<td>0.49 (0.55)</td>
<td>0.85 (2.25)</td>
<td>0.33</td>
<td>0.84</td>
<td>5.90</td>
<td>0.83</td>
</tr>
<tr>
<td>$t_{empty}$ Avg. (Max)</td>
<td>3.58 (9.25)</td>
<td>1.75 (5.00)</td>
<td>1.59 (5.20)</td>
<td>3.40 (13.35)</td>
<td>1.07 (5.20)</td>
<td>1.07</td>
<td>2.28</td>
<td>13.35</td>
<td>3.55</td>
</tr>
<tr>
<td><strong>Most Frequented Location</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visits/second</td>
<td>1.25</td>
<td>0.95</td>
<td>1.70</td>
<td>2.00</td>
<td>1.80</td>
<td>0.95</td>
<td>1.54</td>
<td>2.00</td>
<td>0.43</td>
</tr>
</tbody>
</table>

(SPIE 2012)
Dwell Time Computation

- $k$ – Discrete time variable, associated with an US image frame and corresponding FB position in that frame.
- $B_k$ – The set of voxels occupied by the FB and capture range at time $k$.
- $V$ – The set of voxels the FB has vacated between its previous and current positions: $(B_{k-1} \setminus B_k)$.
- $E$ – The set of voxels the FB has entered between its previous and current positions: $(B_k \setminus B_{k-1})$.
- $N$ – The set of voxels the FB has neither vacated nor entered between time $k-1$ and $k$; in other words the set of voxels that are either vacant in both frames or occupied in both frames: $\neg((B_{k-1} \cup B_k) \cup (B_{k-1} \cap B_k))$.

Only voxels in $(V \cup E)$ need be examined in each frame $k$; specifically,

- $t_{entry}(v) = k \forall v \in E$.
- $t_{dwell}(v) = k - t_{entry}(v) \forall v \in V$.

($t_{dwell}$ is accumulated and divided to produce an average).

Voxels in $N = \neg(V \cup E)$ remained unchanged between frames.
Multiple Candidate Capture Locations

- Selection of capture location based on
  - Workspace obstacles
  - Reachability of robot
  - Time

- Secondary locations

<table>
<thead>
<tr>
<th>Distance Between Candidate Capture Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Distances in mm)</td>
</tr>
<tr>
<td></td>
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<tr>
<td>(A)</td>
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<tr>
<td>-------</td>
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Time Evolution of Capture Location

- How long do we need to monitor to determine a capture location?
- Similarly, how well can we determine a capture location at time $t$?

Capture Locations Computed Online

Spatial Probability  Dwell Time  Visit Frequency

(Hamlyn 2012)
CCL1: Spatial Probability vs. Time

- Spatial probability known after 20 sec (depends on capture range)

(Hamlyn 2012)
CCL2: Dwell Time vs. Time

- Dwell time is known after 5-6 sec

(Hamlyn 2012)
CCL3: Visit Frequency vs. Time

- Visit frequency is known after 15 sec

(Hamlyn 2012)

Question remains: How much is “good enough”?
Robotic Retrieval, Take 2

Ultrasound System

TCP/IP

Workstation Computer

TCP/IP

Other Imaging (C-arm)

Linux RTAI

TCP/IP

Dexterous Robot

FireWire

End Effector

Probe

Beating Heart Phantom
LARS-Snake High Dexterity Robot

- End disc
- Spacer discs
- Base disc
- Primary backbone (central)
- Secondary backbones (outer)
Retrieval Experiments

Goal: To demonstrate the ability to use 3D ultrasound for real-time analysis of the motion of a foreign body in a beating heart phantom, and to guide a dexterous end-effector to capture it.

1. Preoperative registration: Snake robot-US probe-phantom
   - Guide robot to known positions
   - 3DUS of phantom, robot, [fiducials]
   - [CBCT of phantom, robot, fiducials, probe]
2. With heart phantom active, identify foreign body in 3DUS
3. Guide into heart phantom via teleoperation
4. Track foreign body and compute capture locations in real time
5. When a capture location is found, guide robot for capture
6. Determine if/when foreign body is captured; record time
Ambushing > Chasing

- Robotic retrieval experiments (work in progress)
- Further study of fragment motion
  - Conditional probability of subsequent locations
- Improved visualization and tracking methods for different targets
- Robustness to special conditions (e.g. targets leave field of view)
- Heart structure tracking and virtual fixtures
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Questions?