Lecture 11:
Port placement in robot-assisted minimally invasive surgery

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most slides courtesy of Pierre Dupont and Mahdi Tavakoli

case study/research results from:
coronary artery bypass graft (CABG)

CABG is a surgery to restore blood flow to the heart muscle. This is done by using blood vessels from other parts of the body to make a new route for blood to flow around blocked coronary (heart) arteries.
CABG steps

1. The heart is stopped and a heart-lung machine is connected to the patient.

2. An artery is taken from the chest wall, or a section of vein is removed from the leg. This “donated” section of vessel will be used as the bypass.

3. The new vessels is connected (grafted) to the blocked arteries. One end will be attached just above the blockage. The other end will be attached just below the blockage.

4. Electric shocks are used to start the heart beating again and the heart-lung machine is disconnected.
non-robotic approach

requires access via: Median Sternotomy, Mini Sternotomy, or Anterior Thoracotomy

http://www.heart-valve-surgery.com
case study: algorithmic port placement for robot-assisted CABG

two procedures need to be done robotically:

1. harvest the left internal mammary (or thoracic) artery (LIMA)

2. anastomosis of LIMA and coronary artery

study authors: Pierre Dupont (BU, now Harvard Children’s), Jeremy Cannon (CHC), Shaun Selha (BU), Jeff Stoll (BU), Robert Howe (Harvard), David Torchiana (MGH)
the required workspace for the surgical instrument is a challenge

the tool workspace must include
• The underside of the chest wall for takedown of the LIMA
• The surface of the heart in the middle of the chest, where the LIMA is sutured to a blocked heart vessel

Challenge: How to reach this relatively large workspace through a single triad of intercostal ports (one endoscope + two instruments)

Port location directly influences access to the surgical sites, dexterity of the surgical instruments, and instrument collisions
how are the port locations selected?

in the literature:
templates

in practice:
surgeons use external landmarks and size of patient’s torso to make their best guess

proposed:
given a set of internal surgical sites and knowledge of the optimal relative instrument and endoscope angles, determine where each port should be positioned in the chest wall
summary of challenges

port location problems

1. Inability to reach the surgical site
2. Inability to perform the surgical procedure due to the orientations of the tools with respect to each other and the surgical site
3. Internal instrument / endoscope collisions

robot location problems

4. Robot singularities and joint limits
5. Robot collisions

not addressed in this case study
proposed approach

solve port placement and robot placement problems independently

Zeus surgical robot (no longer commercially available)
quality of a given port location

✓ preserve surgeon’s intuition by maintaining hand-eye coordination
✓ orient instruments by task and with respect to the surgical site (i.e. employ relative angles that facilitate suturing, dissection, etc.)
✓ avoid internal collisions between the instruments and the endoscope
✓ permit flushing of endoscope lens
✓ minimize the amount of the endoscope inserted into the chest cavity

Invasive (open-chest) CABG
surgical site coordinate frame

the optimal orientations of the instruments and endoscope can be defined with respect to a coordinate frame whose origin is placed at each internal surgical site.

Instrument Angles

$\theta = \text{Yaw angle in instrument plane}$

$\gamma = \text{Elevation angle of instrument plane}$

Endoscope Angles

$\phi_\alpha = \text{Azimuthal angle}$

$\phi_e = \text{Elevation angle}$

$\phi_o = \text{Constant offset angle}$
how are optimal angles found?

optimal angles are based on a surgeon’s experience in performing CABG:

- Instrument angles are task based
- Endoscope angles are viewpoint based

<table>
<thead>
<tr>
<th>Angle</th>
<th>Angle Weighting</th>
<th>( \psi_{opt} ) (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta_r )</td>
<td>1.40</td>
<td>LIMA takedown: 60, Anastomosis: 60</td>
</tr>
<tr>
<td>( \gamma_r )</td>
<td>1</td>
<td>LIMA takedown: -20, Anastomosis: 45</td>
</tr>
<tr>
<td>( \theta_t )</td>
<td>1.40</td>
<td>LIMA takedown: 60, Anastomosis: 60</td>
</tr>
<tr>
<td>( \gamma_t )</td>
<td>1</td>
<td>LIMA takedown: -20, Anastomosis: 45</td>
</tr>
<tr>
<td>( \varphi_e )</td>
<td>1.67</td>
<td>LIMA takedown: 7, Anastomosis: 52</td>
</tr>
<tr>
<td>( \varphi_a )</td>
<td>1</td>
<td>LIMA takedown: 0, Anastomosis: 0</td>
</tr>
</tbody>
</table>

Endoscope offset angle \( \varphi_e = 30^\circ \).
how are optimal angles found?

optimal angles are based on a surgeon’s experience in performing CABG

- Instrument angles are task based
- Endoscope angles are viewpoint based

LIMA take-down

Anastomosis
dexterity (quality) metric

sum, over all surgical sites, of the weighted squared “distance” of the instruments and the endoscope from their optimal orientation angles

\[
J = \sum_{i=l}^{n} K_i (\psi_i - \psi_{opt})^T W (\psi_i - \psi_{opt})
\]

\(W\) = diagonal weighting matrix to take into account relative importance of different angles

\(K_i\) = weighting factor to account for relative importance of different surgical sites

\(\psi_i = (\theta_r, \gamma_r, \theta_l, \gamma_l, \phi_e, \phi_a)^T\)

\(\psi_{opt}\) = vector of optimal orientation angles
cost function minimization

 technique used in this case study: brute force!

“the ribs, diaphragm, and other anatomic structures limit candidate port sites to a modest number (< 200). Because the weighting matrix is diagonal, the ranking of each port in the triad is uncoupled; thus, an exhaustive comparison of $m$ feasible ports requires only $3m$ evaluations of [the cost function]”

what are other ways to minimize a cost function?

what might concern you about this general approach?
5. locating ports on the patient

1. CT scan
2. image processing
3. surgical planning system
4. operating room registration
System evaluation

- thorax model: ribs with neoprene skin
- task: vessel dissection
- 3 mm diameter “vessel” of stiff clay encased in “soft tissue” matrix of modeling dough and then shrink wrapped.
- three dissections: two at extremes of LIMA takedown and one at site of coronary artery.
system evaluation

- six staff cardiac surgeons
  (Division of Cardiac Surgery, Massachusetts General Hospital, Boston, MA)

- three sets of ports compared:
  1. LIT = template from literature
  2. SURG = cardiac surgeons with thoracoscopic and minimally invasive surgery experience
  3. ALG = algorithmic port placement

■ = Endoscope Port
● = Instrument Ports
dissection speed

![Bar chart showing dissection speed for Proximal, Distal, Coronary, and Mean with literature, surgeon, and algorithm data.](chart.png)
length of gouges > 1.5 mm deep
summary

• decoupled robot placement from port placement
• developed a dexterity metric based on optimal orientations
• preliminary in vitro trials
  • dissection speed increased 25%
  • gouge length decreased 50% or more
long-term role of algorithmic port placement

- routine use versus special cases?
- image library comparison of algorithmic port selections
- development of new procedures
  - e.g., beating heart
discussion

• what do you think about the method for choosing optimal orientations of the instruments and endoscope?

• what are other ways that port placements could be evaluated?
What you will do in Assignment 5: Phantom Omni and “patient body wall”

$p_1$, $p_2$, and $p_3$ are known points in the patient frame $\{B\}$

touch patient points with stylus tip to register $\{A\}$ and $\{B\}$

attempt control through different ports and pick the best one