Towards Multi-Modal Image-Guided Tumour Identification in Robot-Assisted Partial Nephrectomy

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Overview

1. Robot-Assisted Partial Nephrectomy (RAPN)

2. Image-Guidance System for Robotic Surgery

3. Conclusion
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1.1. Kidney & Cancer

- Kidney anatomy
- Kidney function: filter blood
- Kidney cancer:
1.2. Partial vs. Radical Nephrectomy

- Renal mass > 4cm => radical nephrectomy
  + simple surgical procedure

- Renal mass < 4cm => partial nephrectomy
  + avoidance of renal insufficiency
  - possible recurrence

🚫 Challenge: Remove all cancerous tissue while sparing as much healthy tissue as possible to preserve kidney function and avoid recurrence
1.3. Steps of Partial Nephrectomy

Courtesy of Intuitive Surgical Inc.
1.4. Open vs. Minimally Invasive Surgery

- Less blood loss
- Less infections
- Faster recovery time
- Esthetic

For robotic surgery:
- dexterity/precision
- ergonomy
- enhanced 3D vision
1.5. Robotic Surgery

Slave

Surgeon’s Console View

Stereo-Endoscopic Camera

Master

Augmented Reality

Kidney

Tumor

Pre-Operative Scan (CT/MR)

Intra-Operative US

MECBME’14
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2. Image-Guidance System for Robotic Surgery

- Pre-Operative CT/MR
- Stereo Endoscopic Video
- Laparoscopic US
- Segmentation
2.1. Pre-Operative CT Segmentation

- Localize structures of interest in pre-operative scans
- Semi-automatic probabilistic segmentation based on Random Walker [Grady, 2006]
  - *Input*: seed points for each class (kidney, tumour, background)
  - *Output*: probability map to belong to a class

=> Segmentation + Uncertainties/Confidence
2. Image-Guidance System for Robotic Surgery

- Biomechanical Modeling
- Segmentation
- Pre-Operative CT/MR
  - Stereo Endoscopic Video
  - Laparoscopic US
2.2. Biomechanical Modeling of Deformations

- Predict deformations between pre-operative scan and surgery due to change of:
  - patient position (gravity)
  - pressure during insufflation (surfaccic force load)

- Finite element method (FEM) using SOFA platform (with corotational tetrahedral formulation and a Eulerian implicit solver)

\[
M \ddot{u} + C \dot{u} + Ku = F
\]

where  \( u \) = displacement
\( M \) = mass \quad \( C \) = stiffness
\( K \) = damping \quad \( F \) = external force

=> Improvement of tumour localization prediction by 29%
2. Image-Guidance System for Robotic Surgery

- Biomechanical Modeling
- Segmentation
- Pre-Operative CT/MR
- Surface Reconstruction
- Stereo Endoscopic Video
- Laparoscopic US
2.3. Stereo Surface Reconstruction

- Build surface of actual surgical scene from stereo endoscopic camera

  - Improvement of robustness [Bernhardt, 2012]
  - Improvement of accuracy (+56%) using shape prior [Amir, 2013]

  ![Left camera](image1)  ![w/o shape prior](image2)  ![w/ shape prior](image3)

  - Improvement of computation speed (up to x56) with GPU [Islam, 2013]
2. Image-Guidance System for Robotic Surgery

- Multi-Modal Registration
  - Biomechanical Modeling
  - Segmentation
  - Pre-Operative CT/MR
  - Surface Reconstruction
  - Stereo Endoscopic Video
  - Laparoscopic US
2.4. Pre- and Intra-Operative Image Registration

- Align in the same reference frame
  CT segmentation and stereo endoscopic video

- Match 3D model projection with boundaries
  of kidney and tumour in left and right camera

Initial Pose  Rigid Registration  Deformable Registration  Video Sequence
2.4. Pre- and Intra-Operative Image Registration

Robustness to noise compared to active contours without edges (ACWOE)

Accuracy (DSC=dice score) between rigid, linear, non-linear, non-linear + cam. param.
2. Image-Guidance System for Robotic Surgery

- Augmented Reality Visualization
- Multi-Modal Registration
  - Biomechanical Modeling
  - Segmentation
  - Pre-Operative CT/MR
  - Surface Reconstruction
  - Stereo Endoscopic Video
  - Laparoscopic US
2.5. Augmented Reality Visualization

- Guide surgeon in localizing tumour boundaries

- Simple way to display uncertainties without obstructing surgeon’s view

Mesh of most probable boundary
Most probable contour
Range of iso-probabilities
Color-coded uncertainties [Amir, 2013]
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Summary of Contributions:

- Proof-of-concept framework for uncertainty encoded augmented reality system that fuses pre-operative data into surgical scene
- Collection of valuable patient data in the context of RAPN: CT/MR/US + laparoscopic US + stereo video + annotations

Future Work:

- Use laparoscopic US
- Compute and fuse uncertainties from all steps
- Biomechanical modeling during surgery
- Full system integration and validation
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