Robot-Assisted Image-Guided Prostate Interventions

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NSF-Funded Engineering Research Center for Computer-Integrated Surgical Systems and Technology
Long List of Contributors…

• Multi-institution, multi-disciplinary center
  – Johns Hopkins University + Medical Institutions
  – MIT + Brigham & Women’s Hospital
  – CMU + UPMC
  – Others: Morgan State, Georgetown, Harvard, UPenn

• Current funding $6.8M/year
ERC Mission Statement

Develop basic science, technology, and systems working cooperatively with physicians to significantly change the way surgical interventions are carried out in the 21st century.

Couple Information to Action
Computer Integrated Surgery

Preoperative

Computer-assisted planning

Patient-specific Model

Update Model

Update Plan

Computer-Assisted Execution

Intraoperative

Postoperative

Atlas

Patient

Computer-Assisted Assessment
Surgical CAD/CAM Paradigm

Preoperative
- Computer-assisted planning
- Patient-specific Model

Intraoperative
- Update Model
- Update Plan
- Computer-Assisted Execution

Postoperative
- Surgical "TQM"

Surgical "CAD"

Surgical "CAM"
Close The Loop in OR: Robot-Assisted “Point & Click” Surgery

Physician

Digital images

Bot

Planning & control computer

Coordinates

Patient

Imager: CT, MRI, US, X-ray

CT, MRI, US, X-ray
Current Focus: Conceptually “Needle-Based” Localized Procedures
Why Needles?

• Potentially significant impact on medical practice
  • Minimally invasive (compared to open surgery)
    • Faster recovery
    • Less morbidity
    • Fewer complications
    • Lower cost
    • Repeatable in many indications
  • Sharply increasing number of procedures

• Challenging but doable
  • Constrained process – formally describable
  • Major challenges (in addition to open/lap surgery):
    • no visibility
    • no access
    • no room to maneuver
    • no room to recover
Clinical Scope of Our Investigation

<table>
<thead>
<tr>
<th>Prostate</th>
<th>Liver</th>
<th>Spine</th>
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<tbody>
<tr>
<td>200,000 cancers/year</td>
<td>Metastasis from colorectal cancer</td>
<td>$120 billion cost</td>
</tr>
<tr>
<td>1M biopsies /year</td>
<td>130,000 new /year</td>
<td>70% of population affected in lifetime</td>
</tr>
<tr>
<td>10M BPH currently</td>
<td>60,000 death /year</td>
<td>United States numbers</td>
</tr>
<tr>
<td>25% of men affected in</td>
<td>Hepatitis worldwide</td>
<td></td>
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<tr>
<td>lifetime</td>
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</table>

Bone

400,000 metastatic cases/year

Why these?

- Significant health problems
- Right mix of challenge and doability
- Clinical buy-in
- Experience of investigators
- Funding opportunities
Benchmark procedure: TRUS-guided prostate brachytherapy
Accuracy, Consistency, Optimization – Image-Guided Robot Inside Scanner

1. **Physician**
2. **Planning & control computer**
3. **Digital images**
4. **Robot**
5. **Imaging Scanner**
6. **Patient**

**Spatial co-registration between robot and scanner**
Remote Center of Motion for Needle Placement

Benefits
- Suits workflow
- Decoupled motion
- Safe
- Modular

Rotation about stationary fulcrum point

1. 3D translation “move needle to entry”
2. 2D Rotation “orient needle”
3. 1D/2D Insertion “drive needle”
SteadyHand Microsurgery Robot

R. Taylor, D. Stoianovici, L. Whitcomb, A. Barnes
3-DOF Version

- 7-DOF passive arm
- Locking arm
- Table side robot mount
- Amplifier box
- Joysticks and safety switches
- Needle
- 2-DOF Remote Center of Motion robot
- 1-DOF needle injector w/ mounted stereotactic fiducials

Robot: D. Stoianovici
Patient and robot on the table
Patient and robot in CT scanner
Stereotactastic adapter in place
Intra-op treatment planning
Tilted insertion of a needle
Works the same way for kidney, lung...
Transfer to kidney biopsy

Robot registered to CT from a single image using stereotactic frame on the end-effector

Credit: D. Stoianovici, L. Kavoussi, A. Patriciu, S. Solomon (JHU Bayview)
Transfer to lung biopsy

Robot registered to CT using the scanner’s alignment laser
TRUS-guided brachytherapy robot merged with Burdette’s Interplant®

Interplant® FDA-approved treatment planning & monitoring computer system

NIH SBIR grant with Burdette
Practiced on custom-built phantom
The integrated Phase-1 system

Patient  Robot  Robot Control  Robot Supervisor  Treatment planning & monitoring computer

Ultrasound

Physician
Tilted needle to avoid pubic arch interference
Needle tracked in live US image
Real-time dosimetry upon release of seed
Phase-1 results

• Reached all relevant locations
• Demonstrated arbitrary entry and angle
  • **Aiming error:**
    • ~ 2.0 mm
    • worst case 2.5 mm
    • 80% in 2 mm margin
  • **Depth error:**
    • ~ 2.5 mm
    • worst case 5.0 mm
    • 70% in 2.5 mm margin
Phase-2 NCI grant to build compact robot

Interplant® FDA-approved treatment planning & monitoring computer system

NIH SBIR grant with Burdette
Fusion of C-arm and TRUS in Burdette’s Interplant®

Interplant® FDA-approved treatment planning & monitoring computer system

NIH SBIR grant with Burdette

X-ray can see seeds

TRUS can see prostate

Physician

Patient

Ultrasound
C-arm in surgery

- Mobile
- Real-time
- Inexpensive
- Broad coverage
- 60% of brachytherapy practitioners have one

- Limited rotation
- X-ray dose
- Need for calibration
- Low soft tissue contract
- Need for tracking

Courtesy of Siemens
Procedural flow with C-arm augmentation

TRUS imaging → Update plan → Insert needle

TRUS feedback after each needle

Fluoro after a batch of needles
Integrated System Design

Pre-op Calibration

Intra-op Fluoro

3D Cloud of Seeds

Intra-op TRUS

Currently available in Interplant®

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Engineering Research Center for Computer Integrated Surgical Systems and Technology
Problem 1: Organ motion and deformation during TRUS imaging

Deformed Prostate

Relaxed Prostate

Few possible fiducials:
- Active seeds
- Marker seeds
- Implant needles
- Stabilizer needles
- Urethral catheter

Fiducials dislocate relative to prostate anatomy
Problem 2: C-arm tracking a.k.a. pose encoding

Need to know where the X-ray shots are coming from relative to one to another
Our approach: transrectal sheath with mounted 6-DOF fiducials
Pose encoding with helical fiducial

- All six degrees of freedom of the helix can be computed from one projection of the Helix
- By Fixing the Helix to the TRUS stepper → Know transformation between every X-ray picture and TRUS.
Sheath fixed to TRUS stepper base

- X-ray Fiducials
- Sheath
- Air Channel Cover
- Sheath Mount to TRUS stepper
- Sheath-Stepper Quick Release Mount
Pose encoding validation results

**Z-axis Rotation**
- Average Error 0.2°
- Max Error 0.7°

**Y-axis Rotation**
- Average Error 0.58°
- Max Error 1.7°
Auto-segmentation of RUF fiducials
Acoustic coupling in sheath with condom and gel
Acoustic coupling experiments on standard phantom

Bare TRUS Probe

Probe w/ condom

Probe w/ condom + Sheath
Sheath with depressurizing air channels

Exploded View of Channels

8 Air Channels

X-ray Fiducial
Universal C-Arm dewarping/calibration kit
TRUAP – Transrectal Ultrasound-Guided Ablation of the Prostate

Industry Partner: Acoustic MedSystems / Burdette Medical

Funded by Acoustic MedSystems / Burdette Medical
NIH Fast-Track STTR pending w/ Burdette
Helical 4-DOF transrectal robot built around the TRUS probe

The needle can be driven through a curved path (even beyond the limit of elasticity) as long as it comes out in a controlled trajectory.

2D needle insertion/rotation actuation (currently manual)

Stabilizing third-sheath

Needle guiding half-sheath with helical needle path
Burdette’s HIIU Ablator

ACOUSTiC™ (Ultrasonic)

Thermal coagulation achieved in 5 minutes. Lesions of thermal coagulation produced in vitro with three applicators demonstrating conformal control of energy and heating (cross-sectional slices), in bovine muscle, in-vivo. Note the clear demarcation of thermal coagulation achieved in 5 minutes.

It is enough to deliver the needle nearby the target volume, because the placement error is compensated electronically.