Robot-Assisted Image-Guided Needle Placement

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Overview

- Needles Everywhere
- CT-Guided Insertions
- Interventional Ultrasound
- In-MRI Prostate Interventions
- Needle Steering

Surgical CAD/CAM Paradigm

Surgical “CAD” — Surgical “CAM” — Surgical “TQM”
Point & Click Intervention
When robot and patient meet in an imaging scanner in an intervention

Sensible Scope: Needles

Why Needles?
Because they are everywhere 😊

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

Challenging but also 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

<table>
<thead>
<tr>
<th>PROSTATE</th>
<th>MICRO SCALE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prostate</td>
<td>200,000 cancers/year</td>
</tr>
<tr>
<td>Liver</td>
<td>Metastasis from colorectal cancer</td>
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<tr>
<td>Eye</td>
<td>70% of population affected in lifetime</td>
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Why these?
- Significant health problems
- Right mix of challenge and doability
- Clinical buy-in
- Experience of investigators
- Funding opportunities

The System We Want

- Functionally adequate
- Simple
- Inherently safe
- Approvable
- Some critical factors
  - Robot
  - Imager
  - Registration
  - Tissue & Access

Serial Linkages

Pros:
- Can move virtually anywhere
- Lots of different motions
- Smooth motion
Cons:
- Hard to constrain
- Safety concerns
- Complex control
- Ugly math
- Aggregating errors
- "Must do everything to do anything"

United States numbers

**Eye**
- ~100k/y retinal occlusions,
- >100k/y age-related macular degeneration (AMD)

**Ear**
- Hearing loss of 30-35% of 65-75 yo
- 40-50% over 75 yo

**Prostate**
- 200,000 cancers/year
- 1M biopsies/year
- 1M BPH currently
- 25% of men affected in lifetime

**Liver**
- Metastasis from colorectal cancer
- 100,000 new/year
- 60,000 death/year
- Hepatitis worldwide

**Spine/Bone**
- 70% of population affected in lifetime
- 400,000 metastatic cancer/year

**Kidney**
- 130,000 new/year
- 60,000 death/year

**Ent**
- 200,000 cancers/year
- 1M biopsies/year
- 1M BPH currently
- 25% of men affected in lifetime

**Brain**
- 30-35% of 65-75 yo
- 40-50% over 75 yo
Decoupled Linkages
Where joints can move selectively

Pros:
- CAN BE INHERENTLY SAFE
- Separates steps of surgery
- Easy to constrain
- Simpler control
- Simpler Math
- Curved error aggregation

Cons:
- Limited types of motions
- Limited trajectory
- Ragged motion

Example: 3DOF RCM-PAKY

Example: Accubot

Credit: Stoianovici et al.
Example: El Cheapo RCM

- Inexpensive
- Resizable
- Mass-Producible
- Possibly disposable

Credit: Lee, Webster, Kapur, Simaan, Taylor

Example: Sandwich Robot

- 3x 2DOF or 2x2DOF modules connected via needle guide / ball bearings
  - Positioning: ± 20 mm
  - Angulation: ± 35°
  - Pivot point mechanically defined
- Pre-positioning w/ passive arm

Credit: Gernot Kronreif, Joachim Kettenbach, Martin Fürst, Martin Kornfeld, Wolfgang Pietsch, Michael Vogele, ARC Seibersdorf Research GmbH, Austria

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Challenges in CT Guidance

- Out of plane trajectories
- Intermittent and toxic imaging

CT-Guided Prostate Biopsy

Credit: Stoianovici, Patriciu, Fichtinger, et al.

Single-slice Registration to CT

Closed form: fast and computationally robust

Credit: Susil, Taylor, Masamune et al.
Slicer-based Treatment Planning

CT-Guided 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)
**Intra-Cranial Hemorrhage Removal**

Path planning & robot control

Blind spots
Collision
3DOF insufficient

**CT-Guided Lung Biopsy**

Robot registered to CT using the scanner’s alignment laser

**Motion Tracking in Spine Biopsy**

Tracker
Invasive

Credit: Ellis, Fichtinger, et al.

Credit: D. Stoianovici, L. Kavoussi, A. Patriciu, S. Solomon, JHU Bayview and G. Fichtinger, ERC

Credit: Xu, Cleary, Fichtinger et al.
CT-Guided Biopsy Sandwich Robot

Credit: Gernot Kronreif, Joachim Kettenbach, Martin Fürst, Martin Konelek, Wolfgang Placzek, Michael Vogele, ARC Seibersdorf Research GmbH, Austria

CTF-Guided Lung Biopsy

Register real-time CTF to CT
Then compensate with robot

Credit: Xu, Cleary, Fichtinger et al.

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Challenges in US Guidance

- Operator dependent
- Invasive (deforms tissue)
- No image outside the body

Dual Robot Arm Testbed

Example: Active Needle / Passive US
Virtual RCM

- Needle calibrated to tracker
- Pose from tracker
- 3-DOF Cartesian manipulator
- 2-DOF rotation module
- Unencoded passive arm
- EM tracker (FOB)

“Quasi-decoupled kinematics”

Credit: Boctor, Webster, Okamura, Fichtinger

Tele Echography Systems

Credit: Tim Salcudean et al.
Credit: Degoulange et al.
Credit: Troccaz et al.
Credit: Goldberg, Taylor

Robotic 3D US w/ LARS Robot

Implemented both direct and force compliant modes

Pixel/voxel ratio
- Robot: 1.5 - 1.6
- Freehand: 0.3 - 0.8

Credit: Boctor, Fischer, et al.
Hopkins Phantom & Multisided Tank

- Reduced the number of images by a factor of 10-20 (to 3-4 images)
- Avoid the beam width problem
- Easy to automate

AX=XB Closed Formulation

\[ A = A_2 A_1^{-1} \]
\[ B = B_2^{-1} B_1 \]
\[ AX = XB \]

Phantom Jigs Estimate A Matrix

Method #1
Optical pointer is used to digitize 3D points prior to calibration on the three clear plastic plates forming the phantom (L), and an ultrasound image of one of the plates (R).

Method #2
Probe tracking body
Ultrasound probe
Probe orientation

Still phantoms 😞
Phantomless Calibration & QC

- Intuition 2: In-plane motion can recover full calibration to scale factor, and translation can recover remaining scale factor.

- Phantomless Intra-Operative Calibration
- QC by monitoring calibration matrix

![Image of system setup and calibration matrix monitoring](image)


TRUS-guided Prostate Brachytherapy

![Image of prostate and needle guidance](image)

Ultrasound

Needle-guiding Template

US probe

Prostate

Needles (in)

Needles (out)

Gelled gauze pads filled with radioactive iodine-123 or technetium-99m

Image courtesy of Paul Meskell, Beth Israel, Boston.

Plan versus Result

PRE-OP PLAN

POST-OP RESULT

![Images of pre-operative and post-operative plans](image)

Prepared for Burdette Medical Systems, Inc.

Credit: Bokor, Hager, Fichtinger

Poster 159 (Part 1, pp. 621)
Our Take: Robotic Assistance

Physician

Robot control

Robot

Patient

Ultrasound

Interplant® FDA-approved treatment planning & monitoring computer system

Interplant® JHU

Industry partner: CMS Burdette Medical

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Phase-1 System w/ Accubot™

1-DOF passive arm

2-DOF rotation motion stage

1-DOF Needle insertion stage

Ultrasound probe

Mounting bridge

Ultrasound probe

Ultrasound stepper

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Phase-2 System w/ 4DOF Sandwich

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Needles & Seeds Tracked in TRUS

Needle captured in live transverse image
Seed captured in live sagittal image

Credit: Stoianovici, Whitcomb, Burdette, Fichtinger

Needle Tip Localization w/ Doppler
(Salcudean et al.)

- Actively Vibrate Stylet Extension
  - Triangular wave: frequency=2 Hz, amplitude=2mm
- Use Ultrasound Doppler Detection

Doppler on with needle in plane
Doppler off with needle out of plane
Doppler on with needle out of plane

Credit: Salcudean, Rohling, Okazawa, Ebrahimi

3D TRUS Guided Robot System by
(Fenster et al.)

3D TRUS System
Frame-Grabber Module
3D Display
Dose Planning
3D Image Registration

3D TRUS System

Robot Control Software
Calibration Module
Oblique Needle Tracking
Segmentation

Segmentation process
Segmentation - needles
Segmentation seeds

A465 robot

Credit: Fenster et al., London, CANADA
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Why MRI?

- 1.5M prostate biopsy, 220,000 new cancer
- TRUS imaging misses 20% cancer
- Freehand biopsy may miss <1 cc nodes
The MRI Challenge

- No space
- B0 field

Point & Click System Concept

Pioneering Work at BWH
Prostate biopsy and brachytherapy in 0.5T open MRI by Tempany, D’Amico, et al.

- Few open MRI exist
- Low SNR on 0.5T unit
- Long robot arm
- Active clinical program
- Proved feasibility of MRI
- Excellent R&D testbed
Transperineal Prostate Interventions in 3T MRI Scanner

- Leg support
- Patient
- Robotic needle driver

Transrectal Prostate Interventions in 3T MRI Magnet

- Needle guide
- Intrarectal imaging coil
- Tracking coil
- Movable needle guide

The End-Effector (First Prototype)

- Decoupled 3DOF
  1. Translate
  2. Rotate
  3. Insert needle

End-effector

Prostate
Robot in Routine Clinical Use

- From concept to trials in 22 month
- No severe adverse events (SAE)
- 33 biopsies for biopsy and seed placement
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Needle Steering History

- 2000-2003: Reality-based models of needle insertion
  - (DiMaio & Salcudean TRA '03, Alterovitz, et al., O'Leary, et al. ICRA '03)
- 2003-present: Needle steering modeling and experiments
  - (DiMaio & Salcudean MICCAI '03, Glozman & Shoham MICCAI '04, Ebrahimi, et al. MICCAI '03)
  - Alterovitz, IRDS '03
Bevel-Tip Needle Steering (Okamura et al.)

- Bevel tip asymmetry generates a nonholonomic constraint that allows steering in 6DOF with 2 inputs
- Very flexible Nitinol needles

The End