Development of an MRI-Guided Robotic Prostate Intervention System

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Roadmap

• Context
• Problem definition
• Development process
• Results
• Continuing research
• Future directions
Prostate cancer

- 240,890 new cases in 2011
- 33,720 men were to die in 2011
- 1 in 6 men born today will be diagnosed
- >90% long term survival
- 1.5 million prostate biopsies annually

Contemporary biopsy

Pros:
- Inexpensive
- Widely available

Cons:
- Poor visualization of prostate
- TRUS insensitive to cancer
- Mechanical deformations

Cancers as large as half a sugar cube are routinely missed…
Why MRI?

**Excellent soft tissue contrast**

**Extreme environment**

**DRIVING CLINICAL QUESTIONS**
- Sensitive and specific to PC?
- Good for diagnosis?
- Good for biopsy and therapy guidance?

**ENGINEERING CHALLENGES**
- High magnetic field → no metals
- Narrow and long bore

Accurate biopsy and needle placement under MRI is needed for the answer
Point & click surgery paradigm

Fichtinger et al. MICCAI, 2002
Development process

- Requirement analysis
- Workspace analysis
- Kinematic design
- **Image Guidance (IG)**
- Mechanical design
- Actuation, power, control
- Fabrication
- System integration
- Preclinical testing
- Clinical deployment
Workspace & requirements

- Transrectal access
- Accuracy >> CSC (4mm)
- Needle size OD ~2 mm
- Core: 15mm x 1mm

Main structures around the prostate during MRI-guided transrectal procedure. P=prostate, PB=pubic bone, R=rectum (with an inserted endorectal probe), B=bladder. The image was acquired at U.S. National Cancer Institute during an MRI-guided prostate biopsy session.
Kinematic design

**PROBLEM:** Small tubular space in rectum for end-effector

**APPROACH:** Cylindrical coordinate mapping of prostate $\rightarrow$ three independent decoupled motions are necessary and sufficient

![Diagram showing needle and end-effector](image)

**Decoupled 3-DOF**

1. Translate
2. Rotate
3. Insert needle

*Fichtinger et al. MICCAI, 2002*
**IG: Robot to MRI registration**

**PROBLEM:** Localize the robot in MRI space

**PRIOR ART:** All robots use passive markers – slow update rate

**NEW APPROACH:** Three active imaging antennas in end-effector

- Active antennas localized in MRI space (Dumoulin 1994, Derbyshire 1999)
- Imaging coil around Gad capsule, fast dodecahedral readouts
- 3 markers known in robot and image space allow for coordinate system registration

**PROS:**
- High accuracy (0.2 mm, 0.3 deg)
- High update rate (20 Hz)

**CONS:**
- Uses up channels, vendor-dependent (gradient dewarping)

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Susil *et al.* Radiology, 2003

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Laboratory for Percutaneous Surgery (The Perk Lab) – Copyright © Queen’s University, 2012
**IG: Anatomical imaging**

**PROBLEM**: Signal fading near prostate if only surface coils are used

**NEW APPROACH**: Incorporate endorectal imaging antenna coil in end-effector

**PRIOR ART**: Inflatable endorectal imaging coils are common…

**SALIENT FEATURE**: Sheath holds the antenna; decouples it from moving robot parts; decouples target anatomy from moving parts

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**Susil et al.** Radiology, 2003
Actuation, power and control

- Accurate & fast tracking
- Lenient accuracy req.
- Low speed
- Decoupled kinematics
- Visual servo control
- Manual actuation

Materials:
Acetol, Brass, Copper
Aluminum, Titanium,
Carbon fibre

Year 1 from project inception

Susil et al. Radiology, 2003
Human grade system

Year-2 from project inception

Krieger et al. IEEE TMBE, 2005
[most cited IEEE TMBE paper 2005-2010]
Software system integration

**Objective:** Rapid application prototyping for preclinical and clinical trials

**Approach:** Human Supervisory Control Model instantiated for MRI guided robotic surgery; Build on open source and architecture; take full advantage of 3D Slicer (www.Slicer.org) and underlying ITK, VTK, etc.

Tokuda et al. J. CMIG, 2009
Lasso et al. ImNO, 2011
Patient imaging

Susil et al. J. Urol, 2006
Calibration

Lasso et al. NAMIC, 2010
Modeling

Gao et al. IEEE TMI 2010

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Target planning

Lasso et al. NAMIC, 2010
Population based planning

98% sensitivity
We would miss only 4 cancers out of the 200 if we biopsied those men today

200 prostates w/ whole mount pathology

Shen et al. MedIA, 2004
Zhan et al. IEEE TMI, 2007
Zou et al. MedIA, 2009
Execution

Susil et al. J. Urol, 2006
Real-time monitoring

- Transrectal robotic needle placement
- Monitoring at 10fps

Chowing et al. Prostate, 2006
Verification

Lasso et al. NAMIC, 2010
Verification (close-up)

Susil et al. J. Urol, 2006
**IG: Prostate motion and biopsy error**

**PROBLEM:** Post-insertion confirmation volume must be registered with the pre-insertion planning volume - difficult for deformation, motion, and signal inhomogeneity

**PRIOR ART IN VOLUME – TO-VOLUME PROSTATE MRI REGISTRATION**

- All works on prostate MRI dealt with different anatomical boundary conditions
- Brock *et al.* used biomechanical FEM model to drive deformable registration (needing assumptions on tissue properties and boundary conditions)
- Barrat *et al.* statistical shape models and FEM models to drive intensity based registration
- Tsai *et al.* statistical shape models groups to drive MI registration
- Fenster *et al.* used organ contours; Fei *et al.* used organ contour and FEM model

**Special Challenges**

- Data over 5 years
- 6 trials & protocols
- 3 sites in 2 countries
- MRI (1.5T /3T)
- GE, Siemens, Philips
- Robot system evolved
**Intensity-based registration**

NEW APPROACH: Pure image intensity-based volume-to-volume registration.
No assumption on contours, models or material properties

Maximize the $S$ similarity function by adjusting the $\mu$ transformation parameters

$$\mu_{opt} = \arg \max_{\mu} S(\mu)$$
Similarity metric & optimizer

Similarity metric

Several popular metrics exist: CC, NCC, SSD, **Mutual Information (MI)**
MI does not need known mapping function between the intensities of the different images, only assumes the existence of a probabilistic relationship.
Mattes Mutual Information (MMI) [Mattes2003, Wells1996]

\[
I(\mu) = \sum_i \sum_k p(i, k; \mu) \log_2 \frac{p(i, k; \mu)}{p_M(i; \mu)p_F(k; \mu)}
\]

\(i = \) fixed \((F)\) image intensity;
\(k = \) moving \((M)\) image pixel intensities
\(\mu =\) transformation between images

Optimizers

Gradient descent

Easy to adapt, robust and fast for convex problems. Preferred for rigid registration.

Limited-memory Broyden–Fletcher–Goldfarb–Shannon optimizer with simple bounds (L-BFGS-B)
Handles large number of variables, effective if metric function quadratic near optimum, bounds excessive deformation. Preferred for deformable registration.

Implementations in Insight Toolkit [www.itk.org](http://www.itk.org)

MMI plotted for 2 MRI images (prostate region, no deformation)
Stage 1: Gross alignment (rigid) on PB, P, R → Constraints take effect, irrelevant deformations far from prostate cut off.

Stage 2: Correct for residual decoupled prostate motion (rigid). Post-insertion volume has poor signal gradient in IS → Penalize similarity metric for diverging from Stage-1 translation result.

\[ M_{PMMI} = M_{MMI} + p(v_t - v_{t0})v_{IS} \]

deviation from this translation in the second stage \((v_t - v_{t0})\)

approximately correct along the prostate’s IS axis \(v_{IS}\)
Three-stage registration (cont’d)

Stage 3: Deformable registration on prostate, 3rd order B-Spline transform [Rueckert 1999] (Deformation defined by equally spaced control points; grid resolution determined experimentally.)

VALIDATION: 21 patients, 82 biopsies, prostate compared to manual registration; cases w/ more than 10mm translation were included

RESULT: Prostate contour error < 2 mm in all the images, except extreme outliers. T<60sec
Target Displacement & biopsy error

82 biopsies (21 patients)

Target Displacement (avg.)
Parallel to needle: 4.2
Orthogonal to needle 3.4 mm

Biopsy error

<table>
<thead>
<tr>
<th>Target Displacement (mm)</th>
<th>Needle Placement Error (mm)</th>
<th>Biopsy Error (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>5.9</td>
<td>2.3</td>
</tr>
<tr>
<td>Range</td>
<td>1-13.4</td>
<td>0.1-6.5</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>3.5</td>
<td>1.3</td>
</tr>
</tbody>
</table>

* Biopsies for patient motion > 5mm only

73% of biopsies caused motion either towards SP or IA direction

59% of L (•) biopsies moved prostate to R
39% of R (*) biopsies moved prostate to L
Reason: needle bevel orientation?

Xu et al. MICCAI, 2010
**IG: Prostate motion monitoring**

**PROBLEM:** Prostate motion and deformation due to patient motion. Unfortunately, scanner is **not** controllable, slow in 3D, intermittent stationary 2D images

**NEW APPROACH:** Register 3 orthogonal stationary 2D images to 3D planning volume

Example: one 2D image slice

- **in-plane**
- **out of plane**
Motion monitoring (cont’d)

PRIOR ART (2D/3D, IGT)

- Gill, Fei: MRI, rigid only, single slice, multi-resolution runs, and random restart
- Xu: RT CT, robotic lung biopsy, small target small field, rich in texture, single slice
- Krupa: RT US, robotic image stabilization, rich in speckle, single slice

NEW APPROACH

Assemble slices into sparse volume and register as if it was a proper 3D volume

Tadayyon et al. IEEE TBME 2011
Lasso et al. NCIGT WS, 2011
Motion monitoring results (clinical)

VALIDATION METHOD: 4 clinical cases, prostate compared to manual registration, Hausdorff distance computed [Archip2007]

Before registration                              After Registration

• Detects prostate motion and deformation to 1 mm average
• Speed must improve (faster CPU, GPU...)

<table>
<thead>
<tr>
<th>Case</th>
<th>HD* without registration (mm)</th>
<th>HD* with registration (mm)</th>
<th>Rigid registration time (s)</th>
<th>Deformable registration time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.7</td>
<td>0.6</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>5.1</td>
<td>0.9</td>
<td>23</td>
<td>22</td>
</tr>
<tr>
<td>3</td>
<td>3.1</td>
<td>1.9</td>
<td>15</td>
<td>27</td>
</tr>
<tr>
<td>4</td>
<td>5.2</td>
<td>0.8</td>
<td>22</td>
<td>17</td>
</tr>
<tr>
<td>Mean</td>
<td>3.8</td>
<td>1.0</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

* 95% percentile

Tadayyon et al. IEEE TBME 2011
Lasso et al. NCIGT WS, 2011
Commercial translation

- **RT tracking antennas are gone**
  Passive markers (for intermittent registration) + optical encoders (for relative motion) + strong mounting

- **Commercial biopsy needle used**
  New kinematics (2 rots, 1 ins)
  All manual insertion
  Patient pulled from the bore

**References**

Singh et al. Rad Onc, 2007
Krieger et al. IEEE TBME, 2011
Needle tracking in MRI

PROBLEMS: Needle is seen as a large signal void, the void is displaced depending on needle angle w.r.t. $B_0$ and $B_f$

APPROACH: Measure needle localization error over the work space (done)
Analyze data, derive compensation function (in progress…)

Patient case: needle artifact extended forward by 9mm

Needle void displacement for different needles

Glass needle v.s. Titanium needle

Song et al. IEEE TBME 2012 (accepted)
Fully actuated robotic system

Smart end-effectors

Krieger et al. IEEE TMECH (in press)
Surgical process modeling (SPM)

- Human Supervisor drives the system through SPM
- Each stage associated with a scene rendered in views
- Actors in the scene (images, robot, target, needle…)
- Actors come and go, interact, change in space and time

Diagnostic imaging

Planning imaging

Calibration imaging

Target planning

Monitoring imaging

Execution

Verification imaging

Archival

Lasso et al. MICCAI WS, 2009
Scene graph, actors and transitions

Scene graph and actors

Scene rendered in multiple views

Transitions in space and time

Lasso et al. MICCAI WS, 2009
The next decade – needs and opportunities

- Currently experimental procedures will require technology to allow for mass deployment (such as MRI biopsy…)
- New applications (virus injections, nano probes, bio-degradable capsules…) will arise
- In-scanner robotic applications will blossom when imaging scanners finally “open up”
- Present image feedback is sub optimal (low res, low update rate)
- New needle materials and needles are desperately needed
- Smart needles with sensory capabilities (for monitoring patient response to therapy, in-situ probing tumor margin during therapy)
- Local steering – miniature steerable probing and delivery devices would be deployed from within needles
- Open source software will have a huge impact on integrating research systems
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