MRI-guided Surgical Manipulator for Minimally-Invasive Prostate Percutaneous Interventions

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MRI-guided Robot for Prostate Interventions

Goal: To improve the efficacy of needle placement using a physician-operated in-room, master-slave robot for MRI-guided prostate biopsy and brachytherapy.

Current design: Eslami & Iordachita 2012

4-DOF Base Robot Prototype
Outline

- Introduction
- Prostate cancer, diagnosis, and treatment
- Robotic surgery: advantages and challenges
- MRI-guided robots for prostate interventions: past and current state
- System concept, design and implementation
- Robot preliminary evaluation
- Accuracy and repeatability assessment
- MRI compatibility tests
- Conclusions and future works
How many men get prostate cancer in each year?

- About 238,590 new cases of prostate cancer recognized in U.S. in 2013.
- About 29,720 deaths was reported from prostate cancer.

Prostate cancer is the most common type of cancer found in American men, other than skin cancer. Prostate cancer is the second leading cause of cancer death in men, behind only lung cancer. One man in 6 will get prostate cancer during his lifetime. And one man in 36 will die of this disease.

Prostate cancer can be a serious disease, but most men found to have prostate cancer do not die from it. In fact, more than 2.5 million men in the United States who have had prostate cancer at some point are still alive today.

Normal and Abnormal Prostate at Examination

Normal prostate is walnut shaped, appears 20–25 grams and typically measures 4 × 2 × 3 cm (1.6 × 1 × 1.2 inches).

BPE is significantly bigger than normal prostate, but retains smooth surface throughout.

Prostate Cancer typically feels like a nodule or a craggy surface in contrast to the smooth surface of BPE.

Diagnosis tests:

- Physical exam including a digital rectal exam (DRE)
- Prostate-specific antigen (PSA) blood test for early diagnosis
- Prostate biopsy
- Imaging tests
- Transrectal Ultrasound (TRUS)
- Bone Scan
- Computed Tomography (CT)
- Magnetic resonance imaging (MRI)
- ProstaScint scan

Treatment approaches:

- Prostate brachytherapy (radioactive seed implantation therapy)
- Cryotherapy
- Minimally invasive prostate robotic surgery

Prostate Percutaneous Interventions

Standard Diagnosis and Minimally Invasive Treatment

**Diagnosis**

Transrectal Ultrasound-guided Biopsy

**Treatment**

Transrectal Ultrasound-guided Brachytherapy

http://www.google.ca/images?q=trus+biopsy&hl
Prostate Percutaneous Interventions

MRI-guidance:

- Excellent soft tissue **contrast**
- **High sensitivity** for detection

Cancer detection rate of US is not adequately visible in US.
MRI-guided Robots for Prostate Interventions

Prior Works: 2006 ... 2012

U of Utrecht, 2010
Harvard, 2007
WPI, 2012
Wolfgang Goethe, 2007
Imperial College, 2006
U of Maryland, 2011
MRI-guided Robots for Prostate Interventions

Prior Works: BWH, JHU, WPI, Queen’s

1st generation
- Fischer et al. 2007-2009
- 3D Slicer interface

2nd generation
- Song et al. 2009-2012
- 4-DOF robot – Dry run

Accuracy in prostate phantom: 2.5 mm [Seifabadi 2012, IJCARS]

In case of robot failure
- 2-DOF “Smart Template” Sam Song @ BWH 2013
- In case of robot failure
Clinically Optimized 4-DOF Base Robot

Robot specifications:
- 4 actuated DOF (X, Y, Rx, Ry)
- Range of motion: X = ± 35 mm; Y = 130±35 mm, Rx, Ry = ±10°
- Resolution of the robot’s motion 0.1 mm or better
- Robot can travel through its range of motion within 30 seconds
- Accuracy at the needle’s tip in air ±0.5 mm or better, in X-Y plane
- Needle insertion’s accuracy at the needle’s tip ± 1.5 mm or better
- Sufficient stiffness and no backlash (if possible)
- Modular design for manual and tele-operated needle insertion
- Compliance with clinical workflow and safety regulations
JHU BRP Robot Protocol Description
Robot Controller (Designed and built at WPI: by Greg. Fischer)
Robot Components

Needle guide, Ultem, 3D printed, detachable, sterilizable

Needle support, Ultem, 3D printed

Brass rods, plastic spherical bearings

Piezoelectric ultrasonic motor

Timing belt transmission

Leg support, plastic, Aluminum, non-magnetic SS, Garolite G-10

Front trapezoid, high-strength (20%) glass-filled Polycarbonate, CNC

Rear trapezoid, high-strength (20%) glass-filled Polycarbonate, CNC

Linear slide table: Aluminum lead screws, plastic anti-backlash nuts, Aluminum shafts, Delrin linear bearings

18G Needle

Needle support, Ultem, 3D printed
Robot Kinematics

Analytical workspace of the front and rear stages. Red circle (Ø 50mm) implies the prostate gland for two different needle positions with 35 mm offset.

Front stage:
\[
\begin{align*}
P_{fL} &= \frac{x_{1f} + x_{2f}}{2} \\
P_{fr} &= h - h_2 + \sqrt{\left(a^2 - \left(\frac{x_{2f} - x_{1f} - b}{2}\right)^2\right)} \\
P_{fL} &= 0
\end{align*}
\]

Rear stage:
\[
\begin{align*}
P_{rL} &= \frac{x_{1r} + x_{2r}}{2} \\
P_{rr} &= h - h_2 + \sqrt{\left(a^2 - \left(\frac{x_{2r} - x_{1r} - b}{2}\right)^2\right)} \\
P_{rL} &= 0
\end{align*}
\]

Needle tip:
\[
\begin{align*}
x_n &= -(L + L_t) \cos \beta \sin \alpha \hat{i} - h \sin \beta \sin \alpha \hat{i} + P_y \hat{i} \\
y_n &= h \cos \beta \hat{j} - (L + L_t) \sin \beta \hat{j} + P_y \hat{j} \\
z_n &= h \sin \beta \cos \alpha \hat{k} + (L + L_t) \cos \beta \cos \alpha \hat{k} + P_y \hat{k}
\end{align*}
\]

* L = needle length, L₁ = insertion depth
Robot Kinematics

Inverse kinematics

\[
P_{xf} = x_n + (L + L_1) \cos \beta \sin \alpha \hat{i} + h_3 \sin \beta \sin \alpha \hat{i}
\]
\[
P_{yf} = y_n - h_3 \cos \beta \hat{j} + (L + L_1) \sin \beta \hat{j}
\]
\[
P_{zf} = z_n - h_3 \sin \beta \cos \alpha \hat{k} - (L + L_1) \cos \beta \cos \alpha \hat{k}
\]

\[
x_{2f} = 2P_{xf} - x_{1f}
\]
\[
x_{1f} = \frac{1}{2} \left[ 2P_{xf} - b - 2\sqrt{a_1^2 - (P_{yf} - h_1 + h_2)^2} \right]
\]
\[
x_{2r} = 2P_{xr} - x_{1r}
\]
\[
x_{1r} = \frac{1}{2} \left[ 2P_{xr} - b - 2\sqrt{a_1^2 - (P_{yr} - h_1 + h_2)^2} \right]
\]

\[
\alpha = \arctan \left( \frac{P_{xf} - P_{xr}}{d'} \right)
\]
\[
\beta = \arctan \left( \frac{P_{yf} - P_{yr}}{d'} \right)
\]

\[
a_1 = 124 \text{ mm, } h_1 = 12 \text{ mm, } h_2 = 25 \text{ mm, } d' = 181.5 \text{ mm}
\]
Analytical Workspace and Motion’s Constraints of the Manipulator

1\(^{st}\) Constraint: \(\left| \frac{P_{xf} - P_{xr}}{d'} \right| < \tan 10^\circ\)

2\(^{nd}\) Constraint:
\[
\sqrt{a_1 - \left( \frac{x_{1f} - x_{2f} - b}{2} \right)^2} - \sqrt{a_1 - \left( \frac{x_{1r} - x_{2r} - b}{2} \right)^2} < \tan 10^\circ
\]

Finite Element Analysis of Stress Concentration

Ultem 1000: Tensile Strength – 114 MPa (16500 psi)

- Top force = 50 N
- Lateral force = 30 N
- Axial force = 50 N

Max. Displacement = 0.17 mm
Max. Displacement = 0.12 mm
Max. Displacement = 0.07 mm

FE Mesh
Robot Preliminary Evaluation

Robot-patient collision evaluation

- Robot manipulator
- Leg supports
- Robot-patient collision

MRI SNR evaluation

- MRI imaging coil
- Saline phantom

SNR experimental setup in 3T MRI scanner (MAGNETOM Verio, Siemens® Co)

Phantom T2 image for SNR test:
- image size 320x320,
- image center 160, 160,
- region of interest size 30x30,
- SNR degradation 6.37%

Design modifications for collision avoidance

V 3.0

h₁^{3.0} - h₁^{3.1} = 26 mm

V 3.1
Clinical Workflow and Robot Sterilization

The intended procedure is performed as follows:

- Place anesthetized patient in patient bed that lies upon the scanner table and contains fiducial frame
- Place draped robot base on patient bed
- Place scanner table with patient bed in scanner and obtain image data
- Load image data into computer workstation and identify target regions
- Register image data to patient bed (i.e. robot coordinates)
- Identify target axis and depth, place depth stop on needle
- Command robot to move to target pose (position and orientation)
- Insert the needle manually while inside the MRI scanner bore
Accuracy and Repeatability Assessment

Repeatability test of 4 sliders gauged by two dial indicators

<table>
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<tr>
<th></th>
<th>FL (µm)</th>
<th>FR (µm)</th>
<th>RL (µm)</th>
<th>RR (µm)</th>
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<tr>
<td>1</td>
<td>-38</td>
<td>26</td>
<td>-75</td>
<td>-64</td>
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<td>2</td>
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<td>-142</td>
<td>-29</td>
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<tr>
<td>MV</td>
<td>-86</td>
<td>-10</td>
<td>-112</td>
<td>-129.6</td>
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<tr>
<td>STD</td>
<td>109.7</td>
<td>114.8</td>
<td>79.7</td>
<td>102.7</td>
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</table>
Range of error for each slider after executing the Homing command - dial indicator reading

Repeatability test of the needle’s reference point, data collected by the tracker system.

Repeatability test of the needle driver with two dial indicators.
Repeatability test of a specific (Home \( \leftrightarrow \) Target 1).
Position of the current Home w.r.t. the initial Home position.

Repeatability test of approaching different targets \text{without} angulation.

Repeatability test of approaching different targets \text{with} angulation.

Repeatability test of a specific target (Home \( \leftrightarrow \) Target 1 procedure), position of the current Home w.r.t. the initial Home position.
MRI Compatibility Evaluation of the BRP Robot

Baseline - Phantom on base platform only

Base with Legrests attached

Robot on base, not connected

Robot on base, controller in room, connected & unpowered

Controller powered on and connected, no motor power

Controller and motors powered, no motion
Motors moving during imaging under closed loop control
Workflow Verification:
Radvision Interface and Communication with the Robot Controller

- Z-frame registration inside the scanner
- RadVision Interface
- Robot Controller Interface

[Images of the Radvision Interface and communication equipment]
Ergonomics / Configuration (MRI Scanner, Philips Achieva 3.0T - 60 cm bore):
Demonstration of the Needle Insertion into the Phantom
Imaging and Comparison

Imaging protocol:
1) T1-weighted Z-frame image

3D VIBE (T1-weighted 3D FLASH with fat selective pre pulse)
TR/TE = 12 ms/2.02 ms
Flip angle = 45deg
Number of averages = 3
Acquisition matrix = 256 x 256
Image matrix = 256 x 256
Field of view = 160 × 160 mm^2
Pixel bandwidth = 399 Hz/pixel
Percent phase field of view = 100%
Inplane phase encoding direction = COL
Slice thickness = 2 mm
Number of slices = 20
Time 2:24

2) T2-weighted image for Initial Scan
2D Turbo Spin Echo
TR/TE = 4800 ms/100 ms
Flip angle = 150deg
ETL = 20
Number of averages = 3
Acquisition matrix = 320 × 224
Image matrix = 320 x 320
Field of view = 160 × 160 mm^2
Pixel bandwidth = 203 Hz/pixel
Percent phase field of view = 100%
Inplane phase encoding direction = COL
Slice thickness = 3 mm
Time 2:48 x 2
3) Needle confirmation image

2D Turbo Spin Echo
TR/TE = 3030 ms/106 ms
Flip angle = 120 deg
ETL = 27
Number of averages = 1
Acquisition matrix = 320 x 205
Image matrix = 320 x 256
Field of view = 240 x 192 mm\(^2\)
Slice thickness = 3 mm
Receiver bandwidth = 260 Hz/pixel

4) Real-time imaging for needle guidance

TrueFISP-based BEAT-IRT TT sequence provided by Siemens
TR/TE: 3.96/1.98 ms
Flip angle: 45 degrees
Matrix size: 128 × 128
Acquisition matrix = 128 x 128
Number of averages = 1
FOV: 200 × 200 mm\(^2\)
In-plane pixel size: 1.6 x 1.6 mm\(^2\)
Slice thickness: 5 mm
Pixel bandwidth 908 Hz/pixel
Baseline | w Legrests | w Robot | Controller (not powered) | Controller (powered, E-stop ON) | Controller (powered, E-stop OFF) | During the Motion
--- | --- | --- | --- | --- | --- | ---
**T1W-FEE**

**T2W-TSE**

Needle

**T2W-TSE-Init**

**TFE-RT-Circle**
SNR results

<table>
<thead>
<tr>
<th>No.</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Baseline</td>
</tr>
<tr>
<td>2</td>
<td>w Legrests</td>
</tr>
<tr>
<td>3</td>
<td>w Robot</td>
</tr>
<tr>
<td>4</td>
<td>Controller (not powered)</td>
</tr>
<tr>
<td>5</td>
<td>Controller (powered, E-stop ON)</td>
</tr>
<tr>
<td>6</td>
<td>Controller (powered, E-stop OFF)</td>
</tr>
<tr>
<td>7</td>
<td>During the Motion</td>
</tr>
</tbody>
</table>

Different states

- T2W-TSE-Needle
- TFE-RT-Circle

T2W-TSE-Needle

TFE-RT-Circle

Laboratory for Computational Sensing + Robotics

Johns Hopkins University
Clinical workflow and targeting accuracy at Brigham and Women’s Hospital (Nov 21, 2013)

- Clinical workflow (Setup: MRI room, Control room)
- Pre-operative z-frame and T2 imaging and planning (6 targets)
- Robot preparation
- Robot control software
- RadVision
- Needle placement and insertion
- Targeting accuracy with scanner (still under progress)
Conclusions

- Designed and developed the second prototype of the MRI-compatible surgical manipulator for the percutaneous transperineal interventions.
- Forward and inverse kinematics equations of the robot were derived and implemented in the controller. Works properly!
- The design procedure including the kinematics optimization of an MRI-compatible surgical manipulator was discussed.
- Finite element study for the structural analysis was performed.
- Initial patient-robot interference was tested and based on that the second prototype was modified and manufactured.
- Sterilizing workflow was discussed.
- Accuracy and repeatability tests of the manipulator were performed.
- Initial MRI compatibility test was carried out at the UMass Medical School.
- Clinical workflow (with the clinical team; surgeon and nurses), MRI compatibility and precision of the robot (with 3T MRI scanner, MAGNETOM Verio, Siemens® Co, 70 cm bore diameter) and SNR degradation will be soon done at Brigham and Women’s Hospital (Last week of November!)
Collaboration

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**Ongoing and Future work:**
- Targeting accuracy
- Clinical workflow
- Pre-clinical test

Robot moving under closed-loop control with encoder feedback to PC

Robot automatically stops at triggered limit switch

Videos provided by Greg Fischer @ WPI
Thank You!