Clinically Optimized Manipulator for In-bore MRI-guided Transperineal Prostate Biopsy

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August 12, 2014
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

Current implementation: JHU, WPI & BWH 2014
Prostate Cancer

- About 233,000 new cases of prostate cancer recognized in U.S. in 2014.
- About 29,480 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.

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

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 **77%-80%**
Seeds are **not adequately visible** in US
MRI-guided Robots for Prostate Interventions

Prior Work: 2006 . . . 2014

- U of Toronto, 2008
- Johns Hopkins, 2007
- Wolfgang Goethe, 2007
- Johns Hopkins, 2010
- U of Utrecht, 2010
- Imperial College, 2006
- Johns Hopkins, 2007
- U of Maryland, 2011
MRI-guided Robots for Prostate Interventions

Prior Work: BWH, JHU, WPI, Queen’s

1st generation
Fischer et al. 2007-2009

2nd generation
Song et al. 2009-2012

Accuracy in prostate phantom: 2.5 mm (1.3 mm robot) [Seifabadi 2012, IJCARS]

3D Slicer interface

4-DOF robot – Dry run

2-DOF “Smart Template”
Sam Song @ BWH 2013

Manual template 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
- Continuity from manual to fully-actuated device
Robot Component Parts

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

Needle support, Ultem, 3D printed

Brass rods, plastic spherical bearings

Piezoelectric ultrasonic motor USR60-S4N, Shinsei Corp., Tokyo, Japan

Timing belt transmission

18G Needle

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

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

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

Protection cover

Current prototype: Generation 3.1

Needle driver
Robot Kinematics

Robot kinematic diagram

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:

\[ P_{sf} = \frac{x_{1f} + x_{2f}}{2} \]
\[ P_{nf} = h_1 - h_2 + \sqrt{a_1^2 - \left(\frac{x_{2f} - x_{1f}}{2}\right)^2} \]
\[ P_{zf} = 0 \]

Rear stage:

\[ P_{sr} = \frac{x_{1r} + x_{2r}}{2} \]
\[ P_{nr} = h_1 - h_2 + \sqrt{a_1^2 - \left(\frac{x_{2r} - x_{1r}}{2}\right)^2} \]
\[ P_{zr} = 0 \]

Needle tip:

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

* L = needle tip reference length, L_1 = insertion depth
Robot Kinematics

Inverse kinematics

\[ P_{xf} = \bar{x}_n + (L + L_1) \cos \beta \sin \alpha + h_3 \sin \beta \sin \alpha \hat{i} \]
\[ P_{yf} = \bar{y}_n - h_3 \cos \beta \hat{j} + (L + L_1) \sin \beta \hat{j} \]
\[ P_{zf} = \bar{z}_n - h_3 \sin \beta \cos \alpha \hat{k} - (L + L_1) \cos \beta \cos \alpha \hat{k} \]

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

\[ a_1 = 124 \text{ mm}, \quad h_1 = 12 \text{ mm}, \quad h_2 = 25 \text{ mm}, \quad d' = 181.5 \text{ mm} \]
Finite Element Analysis of Stress Concentration

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

Max. Displacement = 0.11 mm

FE Mesh
Max. Displacement = 0.19 mm

Top force = 50 N

Displacement
Max. Displacement = 0.18 mm

Lateral force = 30 N

Axial force = 50 N
Max. Displacement = 0.10 mm

Displacement
Robot Control Architecture

- 4-DOF base manipulator, manual insertion
- RadVision: 510k-approved software developed by Acoustic MedSystems

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Accuracy and Repeatability Assessment

Accuracy and Repeatability Test – Translation – 13 Targets with 12 Relative Distances (T$_1$ - Home) – 8 and 25 Sessions
– all measurements are in mm

<table>
<thead>
<tr>
<th>T$_1$-Home</th>
<th>AVE (X,Y)$_{measured}$</th>
<th>(X,Y)$_{commanded}$</th>
<th>D(distance)</th>
<th>STDEV (X,Y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T$_1$-H (8)</td>
<td>(24.76, 0.02)</td>
<td>(25, 0)</td>
<td>0.24, 0.02</td>
<td>24.77</td>
</tr>
<tr>
<td>T$_1$-H (8)</td>
<td>(24.77, -24.72)</td>
<td>(25, -25)</td>
<td>0.22, 0.28</td>
<td>35.00</td>
</tr>
<tr>
<td>T$_1$-H (8)</td>
<td>(-2.09, -24.97)</td>
<td>(0, -25)</td>
<td>0.09, 0.03</td>
<td>24.98</td>
</tr>
<tr>
<td>T$_1$-H (8)</td>
<td>(25.22, -25.06)</td>
<td>(25, -25)</td>
<td>0.22, 0.06</td>
<td>35.56</td>
</tr>
<tr>
<td>T$_1$-H (8)</td>
<td>(-25.14, -0.09)</td>
<td>(-25, 0)</td>
<td>0.14, 0.09</td>
<td>25.14</td>
</tr>
<tr>
<td>T$_1$-H (8)</td>
<td>(24.38, 24.82)</td>
<td>(-25, 25)</td>
<td>0.62, 0.18</td>
<td>34.80</td>
</tr>
<tr>
<td>T$_1$-H (8)</td>
<td>(0.68, 24.78)</td>
<td>(0, 25)</td>
<td>0.68, 0.22</td>
<td>24.79</td>
</tr>
<tr>
<td>T$_1$-H (8)</td>
<td>(25.73, 24.84)</td>
<td>(25, 25)</td>
<td>0.73, 0.16</td>
<td>35.76</td>
</tr>
<tr>
<td>T$_1$-H (25)</td>
<td>(20.47, 24.81)</td>
<td>(20, 25)</td>
<td>0.47, 0.19</td>
<td>32.17</td>
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<tr>
<td>T$_1$-H (25)</td>
<td>(14.73, -19.69)</td>
<td>(15, -20)</td>
<td>0.27, 0.31</td>
<td>24.59</td>
</tr>
<tr>
<td>T$_1$-H (25)</td>
<td>(-5.26, -4.94)</td>
<td>(-5, -5)</td>
<td>0.26, 0.06</td>
<td>7.22</td>
</tr>
<tr>
<td>T$_1$-H (25)</td>
<td>(-9.93, 18.83)</td>
<td>(-10, 15)</td>
<td>0.07, 0.17</td>
<td>17.86</td>
</tr>
</tbody>
</table>

- Accuracy about 0.73 (mm) in the X and 0.28 (mm) in the Y-direction
- Maximum deviation (error) about 0.28 (mm) in X and 0.21 (mm) in the Y-direction

Accuracy and Repeatability Test – Angulation – 5 Targets – 25 Sessions

| T$_1$-Home | AVE ($\alpha^\circ$, $\beta^\circ$)$_{measured}$ | ($\alpha^\circ$, $\beta^\circ$)$_{commanded}$ | $|\Delta\alpha^\circ|$, $|\Delta\beta^\circ|$ | STDEV ($\alpha^\circ$, $\beta^\circ$) |
|------------|---------------------------------------------|------------------------------------------|-----------------|-----------------|
| T$_1$-H (25) | (5.045, 0.004) | (5, 0) | 0.045, 0.004 | 0.009, 0.003 |
| T$_1$-H (25) | (-0.272, -4.992) | (0, 5) | 0.272, 0.008 | 0.005, 0.003 |
| T$_1$-H (25) | (-4.920, 0.044) | (-5, 0) | 0.080, 0.044 | 0.006, 0.002 |
| T$_1$-H (25) | (0.125, -4.978) | (0, -5) | 0.125, 0.022 | 0.003, 0.012 |

- Maximum error about 0.272° for $\alpha$ and max standard deviation is about 0.01°.
Manipulator MRI-compatibility Assessment

Experimental setup in Philips 3.0 T MRI scanner.

Baseline - Phantom on base platform only
1. Baseline  
2. w Legrests

Base with Legrests attached
3. w Robot (not powered)
4. Controller (powered, E-stop ON)
5. Controller (powered, E-stop OFF)
6. Controller (powered, E-stop OFF)
7. During the motion

T1W-FEE

T2W-TSE Init

T2W-TSE Needle

SNR results

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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

Sterile bag #3818 Microtex Medical, Inc.
Clinical Workflow

Patient ready on scanner table

Z-frame in position

Drape robot, attach needle guide

Slide in robot until hit Z-frame

Lock robot in place

Robot ready for targeting
Thank You!

Future work:
• Get IRB approval for clinical trials (two patient trails successfully done so far)
• Develop a needle driver for automatic biopsy and brachytherapy
• Evaluate feasibility of real-time bevel-tip needle steering

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Gregory Fischer, PhD, Weijian Shang, Gang Li, Nirav Patel - Worcester Polytechnic Institute, MA
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Funding Provided By:
- U.S. National Institute of Health (NIH) grant R01CA111288

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