Clinically Optimal Design and Development of an MRI-Compatible Surgical Manipulator for the Prostate Percutaneous Interventions

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Outline

- Introduction
- Prostate cancer, diagnosis, and treatment
- Robotic surgery: advantages and challenges
- MRI-guided Robots for Prostate Interventions
- Mechanical design: kinematics optimization based on design constraints
- Finite element analysis
- Sterilizing workflow
- Future works and conclusions
How many men get prostate cancer in each year?

- About 241,740 new cases of prostate cancer recognized in U.S. in 2012.
- About 28,170 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.

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

Normal and Abnormal Prostate at Examination

Normal prostate is walnut shaped, approx. 20-25 grams and typically measured 4 × 2 × 3 cm (1.6 × 1 × 1.2 inch)

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

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

Source: http://www.shergillurology.com/
Some Advantages of Robotic Approach vs. Open Surgery

- Less scaring
- Short recovery
- Reduced amount of blood loss
- Less drugs consumption
- Less postoperative catheterization

Source: http://www.cpmc.org/services/surgery/robotic/Robotic-Prostate-Surgery-Advantages.html
MRI-guided Robots for Prostate Interventions


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

First 5-years Cycle (2006-2011)

Aim 1: Robot Development (2-DOF and 4-DOF)

Aim 2: Modeling and Planning (intraoperative image analysis, anatomical modeling)

Aim 3: System Integration (integrating aim1 and aim 2)

Aim 4: Clinical Evaluation

Second 5-years Cycle (2012-2016)

Aim 1: Robotic Assistant (1st year)

Aim 2: Modeling and Planning (2nd year)

Aim 3: System Integration (3rd year)

Aim 4: Clinical Evaluation (4th and 5th years)
MRI-guided Robots for Prostate Interventions

Transperineal Prostate Robot

1st generation

Fischer et al, 2007-2009

MRI-compatible controller

3D Slicer interface

2nd generation

Song et al, 2009-2012

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

NSF Engineering Research Center for Computer Integrated Surgical Systems and Technology
MRI vs. US

- MRI can provide more contrast of soft tissues and distinguish between the normal and diseased tissues
- Useful in early finding of cancer
- MRI can provide 3D image while US is 2D
Collaboration on BRP Robot Project

- Johns Hopkins University
- Worcester Polytechnic Institute (WPI)
- Brigham and Women’s Hospital – Harvard Medical School
- Queens University

Specific Aims:
1- Robot development
2- Modeling and planning
3- Robot controller hardware
4- Robot interface software
5- Navigation software
6- System integration
7- Clinical evaluation
Objectives of the First Generation of the Robot

1- Actuated needle guide for manual needle insertion
   - Guide accurate manual placement of 18G needle in in-vivo human tissue inside 3T MRI scanner in a predefined position with less than 1 mm error (in air)
   - Enable performing biopsy of in-vivo human tissue with the same spatial accuracy
   - Enable performing brachytherapy seed insertion into a predefined pattern of no more than 2 mm granularity. These procedures will use MRI imaging modality to identify the target regions

2- Actuated needle guide for automatic needle insertion
JHU BRP Robot Protocol Description

Pneumatically Operated MRI Robot for Diagnosis and Treatment of Transperineal Prostate
BRP Robot Inside the MRI Scanner
Some Principal Advantages of the New Robot Design

- Eliminating the spherical joint and replacing for a parallelogram mechanism to control the needle.
- Using lead screw tables for the movement of the front and rear trapezoid stages.
- Applying anti-backlash nuts in the screws to remove backlash.
- Possessing more space for angulation of the needle.
- Having the option for automatically needle insertion.
- The workspace can cover a circle with diameter about 70 mm (compatible with the interior bore of Siemens MAGNETOM Verio 3T Siemens A.G.) which is large enough to cover the prostate gland around 50 mm.
- Implementing piezomotors to provide robustness and precision into the system.
- The system has more stability robustness, high dynamics performance, controllability and maneuverability.
- Suitable for the clinical experiment.
Some Expectations of the New Robot Design

- The robot must be able to cover the prostate gland with about **50-60 mm** diameter.
- The robot motion resolution is about **0.1 mm** or better.
- The robot can travel through its range of motion within 30 seconds.
- The base robot accuracy at needle in air must be **±0.5mm** in XY plane.
- The robot needle insertion accuracy at the needle tip in air needs to be less than **1.5 mm** (or 2 mm max.) error along the Z axis.
- The needle insertion task should be done at a maximum speed of **1 cm/sec**.
Kinematics Study

- Each stage has 2-DOF in the vertical plane.
- Overall there is a 4-DOF mechanism.
- Create the needle orientation in the X-Y and X-Z planes.
- These coordinate systems are in accordance with the coordinate system in the MRI scanner for registration.
For the angulation of the needle driver support, there is a point of rotation which is called point “P” and two angles can be defined $\alpha, \beta$

$$\alpha = \text{atan2}\left(\frac{P_{xf} - P_{xr}}{d}\right)$$

$$\beta = \text{atan2}\left(\frac{P_{yf} - P_{yr}}{d}\right)$$
\[
\begin{bmatrix}
P_x \\
P_y
\end{bmatrix}
_i = \begin{bmatrix}
\frac{x_{1i} + x_{2i}}{2} \\
h_1 - h_2 + \sqrt{a_i^2 - \left( \frac{x_{1i} - x_{2i}}{2} - \frac{b}{2} \right)^2}
\end{bmatrix}
\]
Kinematics Optimization Based on Design Constraints

*Initial Design*

H_{Max} = 166\ mm
H_{Home} = 130\ mm
H_{Min} = 96\ mm
D = \pm 35\ mm
25^{\circ} < \alpha < 75^{\circ}

2D Analytical Workspace

\[ \alpha \]

\[ D \text{ (Lateral Motion)} \]

Cartridges
Constraints on Angle

if $\alpha > 75^\circ \Rightarrow$ Unstable Stage!

if $\alpha < 25^\circ \Rightarrow$ Too Much Friction!

Lateral forces

Difficult to lift
First Robot Prototype

Side bar

U-shape stage

Cartridge
Front View

Stationary frame

Prostate Gland

Cartridge

Sliding shaft

Sliding rails to lock the robot in place

Patient Legs
Top View

- Needle
- Power Transmission
- Piezoelectric motors
- Re-designed lead screw tables
- Base robot (4 DOF)
Robot Workspace and Degrees-of-Freedom
Finite Element Analysis of Stress Concentration

FEM Mesh

Displacement

Stress

Strain
FEM Animation for Trapezoid – Displacement

Maximum displacement for all cases is always $< 3.67 \mu m$
MRI Compatible Ultrasound Motor (Shinsei, Corp.)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
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<tbody>
<tr>
<td>Drive Frequency (MHz)</td>
<td>40 [MHz]  ~ 45 [MHz]</td>
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<tr>
<td>Drive Voltage (V)</td>
<td>130 [Vrms]</td>
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<tr>
<td>Rated Output (W)</td>
<td>5.0 [W]</td>
</tr>
<tr>
<td>Maximum Output (W)</td>
<td>10.0 [W] (at Maximum Load)</td>
</tr>
<tr>
<td>Rated Speed (rpm)</td>
<td>100 [rpm]</td>
</tr>
<tr>
<td>Maximum Speed (rpm)</td>
<td>150 [rpm]</td>
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<tr>
<td>Rated Torque (N·m)</td>
<td>0.5 [N·m]  (5.0 [kg·cm])</td>
</tr>
<tr>
<td>Maximum Torque (N·m)</td>
<td>1.0 [N·m]  (10.0 [kg·cm])</td>
</tr>
<tr>
<td>Holding Torque (N·m)</td>
<td>1.0 [N·m]  (10.0 [kg·cm])</td>
</tr>
<tr>
<td>Resonance (ms) (No-load)</td>
<td>Less than 1 [ms]</td>
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<tr>
<td>Direction of Rotation</td>
<td>CW, CCW</td>
</tr>
<tr>
<td>Operational Temperature Range (°C)</td>
<td>-10 [°C]  ~ 45 [°C]</td>
</tr>
<tr>
<td>Temperature Limit</td>
<td>Surface of Stator 70 [°C], Surface of Case 80 [°C]</td>
</tr>
<tr>
<td>Operational Humidity Range (°C)</td>
<td>0  ~ 45 [°C] (without condensation)</td>
</tr>
<tr>
<td>Endurance Time (hours)</td>
<td>1,000 [hours] (Sum of the time when the motor actually moved)</td>
</tr>
<tr>
<td>Weight (g)</td>
<td>250 [g]</td>
</tr>
<tr>
<td>Remarks</td>
<td>Single Shaft</td>
</tr>
</tbody>
</table>

**T-N Characteristic**

- **Continuous**
- **Short Time**

![Graph showing T-N Characteristic](image)
Current Implementation and Workflow
Problem: Small amount of interference between the patient and the robot.  
Solution: Lower the level of the robot by re-shaping the bar links while preserving the same workspace.
Re-designed and Modified Robot
Angulation and Interference Investigation
Finite Element Analysis for Needle Driver Support

F = 1N
Sterilizing Workflow

Procedure:

1. Enfolding the robot manipulator with the sterile plastic drape.
2. Inserting the frontal part of the needle driver support to the needle driver support by using two sets of screws.
3. Place the patient on the patient bed and inserting him into the MRI scanner bore in the supine position.
4. Place the robot manipulator on the patient bed next to the patient perineum and fiducial marker frame.
5. Executing the MR imaging for the needle targeting confirmation.
6. Inserting the needle inside the patient’s prostate.
7. Go to step No. 5.
Future Works

- Building the robot and calibrate it: in progress with %20 glass-filled polycarbonate.
- Design and installation of the needle driver.
- Testing the precision of the robot-needle driver without the controller.
- Implementing a proper control algorithm for the robot control.
- Software development for the robot motion control.
- Robot/image registration in 3D slicer and RadVision.
- Pre-clinical test.
Conclusions

- Comparison between the earlier and current prototypes of the MRI compatible robots was done.
- The design procedure including the kinematics optimization of an MRI-compatible surgical manipulator discussed.
- Initial patient-robot interference was tested.
- Primary advantages of the new robot design were presented.
- Finite element study for structural analysis was performed.
- Sterilizing workflow was demonstrated.
References

- NIH grant proposal, BRP prostate biopsy robot.