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

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07/02/2012
Outline

- Introduction
- Prostate cancer, diagnosis and treatment
- Robotic surgery: advantages and challenges
- Mechanical design: kinematics optimization based on design constraints
- Finite element analysis
- MRI compatible direct drive piezomotors
- Tracking system for MRI guided interventions
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.

*Source: American Cancer society,*
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: Normal prostate is walnut shaped, approx. 20-25 grams and typically measured 4 x 2 x 3 cm (1.6 x 1 x 1.2 inches).
- Benign Prostate Enlargement (BPE): BPE is significantly bigger than normal prostate, but retains smooth surface throughout.
- Prostate Cancer: Prostate Cancer typically feels like a nodule or a rough, surface in contrast to smooth surface of BPE.


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Some Advantages of Robotic Approach vs. Open Surgery

- Less panicking
- 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 vs. TRUS

- 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 TRUS 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

Instructions to Build the BRP Robot Controller Library

- Eliminating proxy between the robot and 3D Slicer
- Developing a robot simulator for:
  - Reading/sending commands from/to the slicer-robot
  - After inverse kinematic calculation, sending proper commands to 3D Slicer
- Updating communication protocol:
  - Replacing all non-standard message types with the standard types in robot controller to follow the MRI new BRP OpenIGTLink protocol
- Re-constructing the robot controller library from the scratch and testing on a new machine

Robot Controller Build Instruction:
Pneumatically Operated MRI Robot for Diagnosis and Treatment of Transperineal Prostate
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 $\pm 0.5$mm 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 Optimization Based on Design Constraints

2D Analytical Workspace

H\text{\_Max} = 166 \text{ mm}
H\text{\_Home} = 130 \text{ mm}
H\text{\_Min} = 96 \text{ mm}
D = \pm 35 \text{ mm}
25^\circ < \alpha < 75^\circ
Constraints on Angle

if $\alpha > 75^0 \Rightarrow$ Unstable Stage!

if $\alpha < 25^0 \Rightarrow$ Too Much Friction!

Lateral forces

Difficult to lift
First Robot Prototype

Side bar

U-shape stage

Cartridge
Front View

- Patient Legs
- Stationary frame
- Prostate Gland
- Sliding shaft
- Sliding rails to lock the robot in place
- Cartridge
Top View

- Needle
- Piezoelectric motors
- Power Transmission
- Re-designed lead screw tables
- Base robot (4 DOF)
Robot Workspace and Degrees-of-Freedom
Second Robot Prototype

Side bar

U-shape stage

Cartridge
Finite Element Analysis of Stress Concentration

**FEM Mesh**

**Displacement**

**Stress**

**Strain**
FEM Animation for Trapezoid – Displacement

Maximum displacement for all cases is always < 3.67μm
MRI Compatible Direct Drive Piezomotors (Actuated Medical, Inc.)

<table>
<thead>
<tr>
<th>Specifications Example</th>
<th></th>
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<tbody>
<tr>
<td>Size</td>
<td>2.7 x 2.7 x 1.4 inches</td>
</tr>
<tr>
<td>(LxWxH - not including shaft)</td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>40 - 45 kHz</td>
</tr>
<tr>
<td>Maximum Speed</td>
<td>225 RPM</td>
</tr>
<tr>
<td>Stall Torque</td>
<td>≥ 2.0 N·m</td>
</tr>
<tr>
<td>Torque @ 100 RPM</td>
<td>≥ 1.5 N·m</td>
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<tr>
<td>Max. Power Output</td>
<td>17 W</td>
</tr>
<tr>
<td>Control/ Tracking</td>
<td>500 PPR encoder available</td>
</tr>
</tbody>
</table>

![Piezomotor images with performance graphs]
The EndoScout® works on ANY scanner.

The location accuracy is 2mm. The orientation accuracy is 1 degree.

The EndoScout® is FDA cleared to use in any MRI guided intervention.

The EndoScout tracking system is installed in hospitals around the world. Among them are: Johns Hopkins Hospital (Baltimore, MD), National Institutes of Health (Bethesda, MD), Massachusetts General Hospital (Boston, MA), Brigham and Women's Hospital (Boston, MA), ...

The installation process takes between one and two days.

They can provide you with an EndoScout® client, which communicates with the EndoScout® main program via TCP/IP. They will also provide you with the source code of the client, which you may integrate in your own program. The EndoScout® client works on Windows and Linux platforms.
Some Clips for Different Applications

- Cryotherapy using the EndoScout® tracking system
  http://www.robinmedical.com/video_cryo.html
- The breast biopsy navigation system
  http://www.robinmedical.com/surgi_breast.html
- Brain intervention navigation system
  http://www.robinmedical.com/surgi_brain.html
- Prostate procedures navigation system
  http://www.robinmedical.com/surgi_prostate.html
- More videos:
  http://www.robinmedical.com/videos.html
Future Works

- Building the robot and its calibration
- Implementing a proper control algorithm for the robot control
- Software development for the robot motion control
- Sterilization drape to be attached/detached without much effort
- Robot/image registration in 3D slicer and RadVision
- Design and installation of the needle driver
- Installation of the needle
- Pre-clinical test
Hypothesis and Design of an Integrated X-Ray/Bioluminescent Imaging (BLI) and Tomography (BLT) for the Study of Radiation and Treatment in Small Animals

Sohrab Eslami
Collaboration with the JHU Radiation Oncology Department
School of Medicine
Outline

- Design and construct an integrated x-ray/bioluminescent tomography (BLT) system that can function as a standalone research apparatus and also on-board the SARRP to guide focal irradiation.
- Enhance the BLT of the system to improve localization by incorporating multi-projection, multi-spectral BL images as well as CT priors.

Functionality:

- Constructing a high resolution, pre-clinical irradiation system that enables the study of radiation response of small, soft tissues targets which are most difficult to localize the Center of Mass (CoM) within 1 mm.
- This system functions under the cone-beam computed tomography (CBCT) imaging guidance.
Integrated X-Ray/BLI System and Specifications

- X-Ray source Kevex PXS10-65W rated at max. 130 kV having a variable small focal spot (10 μm to 100 μm).
- High resolution CMOS detector with 74.8 μm pixel size.
- In-vivo optical tomography scheme consisting of the on-board bioluminescent imaging (BLI) and tomography (BLT).
- Integrating a portable robotic rotational stage system.

Operating Voltage Range: 20 to 130 kV ± 0.5%; > 45 kV to achieve full beam current and meet specifications.
Maximum Power: 65 Watts @ 130 kV
Maximum Beam Current: 0.500mA ± 2%
Spot Size:
- 10μm @ 8 watts, 45-130 kV
- 22μm @ 16 watts, 45-130 kV
- 48μm @ 32 watts, 70-130 kV
- 100μm @ 65 watts, 130 kV

Pixel size: 74.8μm
Sensitive area: 145.4 mm x 114.9 mm
Resolution: 1944 x 1536 pixels
Sensor type: CMOS active pixel sensor
Pixel binning: 1x1, 1x2, 1x4, 2x1, 2x2, 2x4, 4x1, 4x2, 4x4
- A high performance, low noise CCD camera mounted on a light-tight housing along with an optical filter assembly to allow multi-spectral imaging aimed for BLI and BLT.
- The camera-filter-mirror assembly is attached to a motorized gantry to acquire the image in angles between 0° to 90° while the camera does not block the path of the x-ray path.
- A second rotary stage is providing 360° angular rotation for the embraced animal in a housing on top of the stage to facilitate the CBCT through the x-ray source.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PP Typical</th>
<th>Guaranteed</th>
<th>CC Typical</th>
<th>Guaranteed</th>
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<tbody>
<tr>
<td>Travel Range (°)</td>
<td>360 continuous††</td>
<td>360 continuous††</td>
<td>360 continuous††</td>
<td>360 continuous††</td>
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<tr>
<td>Resolution (°)</td>
<td>0.0062††</td>
<td>0.0005</td>
<td>0.0062</td>
<td>0.0005</td>
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<tr>
<td>Minimum Incremental Motion (°)</td>
<td>0.001</td>
<td>0.002</td>
<td>0.001</td>
<td>0.002</td>
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<tr>
<td>Uni-directional Repeatability (°)</td>
<td>0.006</td>
<td>0.01</td>
<td>0.002</td>
<td>0.004</td>
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<tr>
<td>Reversal Valve (Hysteresis) (°)</td>
<td>0.016</td>
<td>0.03</td>
<td>0.012</td>
<td>0.023</td>
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<tr>
<td>Absolute Accuracy (°)</td>
<td>20</td>
<td>50</td>
<td>20</td>
<td>50</td>
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<tr>
<td>Maximum Speed (°/s)</td>
<td>40</td>
<td>60</td>
<td>50</td>
<td>60</td>
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<tr>
<td>Wobble (μrad)</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Eccentricity (μm)</td>
<td>3</td>
<td>3</td>
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<tr>
<td>MTBF</td>
<td>20,000 h at 25% load and with a 30% duty cycle</td>
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</table>
Nikon 60mm f/2.8D AF Micro Nikkor Lens

Galil Controller DMC 2143 with an embedded Amp 20440 to control up to 4 motors

2x Teleconverter extension lens
Principle of Cone Beam Computed Tomography (CBCT)

Reconstructed image of the mouse with the I-Star CBCT software (Dr. Jeff Siewerdsen)

Axis of rotation

Step-by-step rotation ($1^\circ$) from 0 – 360°

Detector Panel

X-Ray Source

X-Ray

Z

Y

X
Interlock Circuit of the X-Ray System
New BLI System with the Previous SARRP System

The Gulmay SARRP with computer controlled gantry and robotic stage motion. A 20 cm x 20 cm flat panel imager facilities Cone Beam CT (CBCT).
BLI System Configuration

CCD Camera
Galil Controller

Detector Panel
X-Ray Source

Calibration Phantom
Mirror System

Optical distance from iso-center to the lens of the camera = 40 cm

3 First surface mirrors
Future Works

- Running the X-ray source in the medical school to measure the radiation leakage and supply the proper shielding for protection

- Performing the X-Ray calibration and CBCT

- Performing the camera calibration by using the “Uniform Source Sphere”

- Integrating the rotary stage controller with the detector panel software to synchronize the rotation of the motor with the panel imaging procedure during the CBCT.
Conclusions

MRI-Compatible Prostate Biopsy Robot

- The design procedure including the kinematics optimization of an MRI-compatible surgical manipulator for prostate percutaneous intervention was discussed.
- Primary advantages of the new robot design were presented.
- Finite element study for structural analysis was performed.
- Motor and power transmission system were discussed.

X-Ray/BLI System

- Components including X-Ray source, detector panel, CCD camera, rotary stage, controller were introduced.
- Complete electric circuit of the X-Ray system was presented.
- Configuration and functionality of the system were presented and discussed.
- X-Ray calibration processes were explained.
References

- System requirements for the BWH BRP robot manual, May 2012
- NIH grant proposal, X-Ray/BLI system
- NIH grant proposal, BRP prostate biopsy robot
- MRI Compatible Direct Drive Piezomotors, Actuated Medical, Inc.
- Tracking System for MRI Guided Interventions, Robin Medical, Inc.
Thank You!