The Ultrasound of MUSiiC: Robotics and Advanced Ultrasound Imaging in Medicine

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### Medical UltraSound for Imaging and Intervention Collaboration (MUSiiC) Research Laboratory

#### Medical Intervention
- Ablative Therapy
- Biopsy Guidance
- External Beam Radiation Therapy
- Robotic Prostatectomy
- Partial Nephrectomy

#### Research Thrusts
- Advanced Ultrasound Imaging (Photoacoustic, Thermal, and Elasticity)
- Co-Robotic Ultrasound Imaging
- Ultrasonically Smart Tools (smart catheter, needles, and probe)
- Ultrasound for Stimulation and Treatment
Co-robotic Ultrasound Imaging

Trunk and neck twist  Trunk flexion

Wrist flexion and “pinch” grip

Challenges on ultrasound imaging:
- Limited image quality and field of view
- Limited reproducibility
- High user dependency
- Work related musculoskeletal pain (MSP) affect 63 - 91% of sonographers

Robotic Ultrasound Solution

Coffin C., Reports in Medical Imaging, 2014.
Co-robotic Ultrasound Imaging

Cooperatively Controlled Robotic (Co-Robotic) Ultrasound
1. Reduce the force applied by the user
2. Stabilize imaging
3. Less user-dependency
4. Without distort or complicate current procedure

The proposed co-robotic system is composed of:
- 6-axis robotic arm
- 6 DOF force/torque sensor
- Detachable handheld US device with 1 DOF load cell
- Ultrasound (US) probe

Co-robotic Ultrasound Imaging System demo – case 1,2 (freehand)

Red Bar: Contact Force
Blue Bar: User’s force
Co-robotic Ultrasound Imaging
System demo – case 3 (Robotic)

Compliant mode

Co-robotic Ultrasound Imaging
System demo – case 4 (Robotic w/ constraint)

Compliant mode
Co-robotic Ultrasound Imaging
Result- Applied Force Reduction

- The robot assistance in case 3 and case 4 reduces the force applied by the human participants from 20 N to an average of 5.48 N and 13.62 N, which are 73 % and 32 % reductions.
**Synthetic-Tracked Aperture Ultrasound (STrAtUS) Imaging Using Robotic Guidance**

- Ultrasound image resolution is determined by focal depth ($F$), center frequency ($f$/$\lambda$), and probe aperture ($D$).
  \[
  \text{Resolution} = \frac{F \cdot \lambda}{D}
  \]
- High frequency is desired for high resolution, but it doesn’t penetrate into deep tissue.
  \[
  p(x) = p_0 e^{-\alpha x} e^{-j\omega(t-x/c)}
  \]
  
  Attenuation coefficient $\alpha \approx \frac{\alpha_0}{\lambda}$
- Probe aperture is the only parameter we can manage to increase if the region of interest is in deep region.

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**Synthetic Aperture**

- Multiple sub-aperture will be synthesized to create a big aperture in transmission and receive.
- However, it is limited by the physical size of ultrasound transducer.
Synthetic-Tracking Aperture Ultrasound

Move the tracked ultrasound transducer

Transmit Sequence

Receive Sequence

Aperture Size

B-mode Image (Deep region)

Robotic Scanning Strategies

Decide initial position

Determine trajectory for multiple passes scanning

Sonographer moves ultrasound probe by following VF

Data Collections

Acquired enough pixels

Yes

No

Synthetic aperture beamformer

Display B-mode image

Co-robotic virtual fixture

Auto-pilot scanning mode
Coordinate Systems and Motion Determination

Robot base to US image frame
1. $\mathit{B}$: Robot base to robot end-effector
2. $\mathit{X}$: Robot end-effector to US image frame

Definition of motion
$$ M = X^{-1}B^{-1}\mathit{B}X $$

Motion to move from pose $i$ to $j$
$$ B_j = B_iXMX^{-1} $$

Translational Motion
$$ B_j = B_iX \begin{bmatrix} 1 & t_M \\ 0_{1 \times 3} & 1 \end{bmatrix} X^{-1} $$
$$ = \begin{bmatrix} R_{Bj} & R_{Bj}Xt_M + t_B \\ 0_{1 \times 3} & 1 \end{bmatrix} $$

Field II Simulation

- Field II is used to simulate acoustic response from a single point target located at 10 cm depth.
- A 64 elements phased array probe with 0.32 mm pitch is simulated, and motions are applied in lateral direction with 10.24 mm interval.

Definition of motion
$$ M = X^{-1}B^{-1}\mathit{B}X $$

Three poses

Five poses

Five poses with error

Simulation of error for a motion
\[ \bar{M} = X^{-1} \Delta X^{-1} B_j^{-1} \Delta B_j^{-1} B_i \Delta B_i X \Delta X \]

- Simulated point source from five poses with error. Rotational error in \( X \) was 0.7 degree, and rotational and translational error in \( B \) was 0.1 degree and 0.1 mm, respectively.

Image Quality Analysis

- We quantitatively evaluated the ultrasound image quality while introducing error in tracking sensor (\( \Delta B \)) and ultrasound calibration (\( \Delta X \)).
- The size of the point spread function is measured by counting the number of pixels over a certain threshold (-25 dB).
- The single pose result was set as the baseline (1), and the ratio of the pixel count compared to the baseline case is used as the metric to express the quality of the image.
- The error vector is randomized while the magnitude of error is fixed.
- Therefore, the effect can vary for the same magnitude of errors.
- 18 different \( X \)s are computed, and Mean, Worst, and Best case are shown.
Image Quality Analysis

Improvement of pixel compared to single pose

Synthetic-Tracked Aperture Ultrasound (STrAtUS) Imaging Using Robotic Guidance

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**Synthetic-Trackerd Aperture Ultrasound (STrAtUS) Imaging Using Robotic Guidance**

**From Auto-pilot to Co-Pilot: Co-Robotic Scanning**

- A Robotiq FT 150 sensor is used to measure the force and torque applied by the user while manipulating the probe.
- The measurements from the FT 150 are then translated into robot joint velocity commands, allowing for compliance or admittance control of the robot.
Co-Robot Control: 
Constrained Optimization Approach

What is Virtual Fixture?
• Virtual fixture is a concept of creating a physical restriction on the motion by constraining the robotic control.

Virtual Fixture Scenarios
1. Stay on a line
2. Stay on a plane
3. Stay on a plane (1DOF rotation)
4. Keep contact force
Synthetic-Trivialed Aperture Ultrasound (STrAbUS) Imaging Using Robotic Guidance

**Left:** Single pose B-mode ultrasound image of general US phantom. **Right:** STRATUS images synthesized in the range of 60 mm motion data; field-of-view expanded by 65.5 mm.

<table>
<thead>
<tr>
<th></th>
<th>Single</th>
<th>STRATUS: 60 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>FWHM (mm)</td>
<td>3.87</td>
<td>2.37</td>
</tr>
<tr>
<td>Contrast (dB)</td>
<td>-7.14</td>
<td>-10.67</td>
</tr>
<tr>
<td>SNR (dB)</td>
<td>25.01</td>
<td>29.35</td>
</tr>
</tbody>
</table>

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Synthetic-Tracked Aperture Ultrasound (STrAbUS) Imaging Using Robotic Guidance

**Single Pose**

**STRATUS**

6x
**Quantitative Ultrasound Imaging: Ultrasound Tomography**

- US tomography reconstructs tomographic images (instead of traditional reflection images) to enable quantitative measurement of acoustic properties.
- Requires transmitter and receiver to be at two opposite sides of the medium.

- http://www.delphinusmt.com/our-technology/softvue-system

**Co-robotic Ultrasound Tomography: First Prototype**

Co-robotic Ultrasound Tomography: Second Prototype

Co-robotic Ultrasound Tomography: Prostate Cancer

Fereshteh Aalamifar, Reza Seifabadi, Peter Choyke, Maria Merino, Peter Pinto, Arman Rahmim, Bradford J. Wood, Emad M. Boctor
Co-robotic Ultrasound Tomography: Prostate Cancer

Mold for patient specific US friendly phantom
US friendly phantom containing prostate
Scanning the ex-vivo prostate

MRI image Tomographic image

Co-robotic Ultrasound Tomography: Prostate Cancer: Initial Results

EM iteration: 50
B-mode image
Co-robotic Ultrasound Catheter Tracking

A New Robotic Ultrasound System for Tracking a Catheter with an Active Piezoelectric Element

Quanli Ma, Joshua Davis, Alexis Cheng, Gregory Chirikjian, Emad Bector

Laboratory for Computational Sensing and Robotics
The Johns Hopkins University

Multiple photoacoustic spots are projected onto the surface of the patient body, generating an acoustic signal due to the photoacoustic effect. A stereo camera and PZT element can simultaneously capture data related to these spots.

Photoacoustic active layer placed on top of pig during in vivo experiment. Mean Reconstruction Precision (2.59 mm), Estimated Accuracy (8.69 mm).

Alexis Cheng, Younsu Kim, Yuttana Itsarachant, Haichong K. Zhang, Clifford R. Weiss, Russell H. Taylor, Emad M. Boctor
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### Active Echo

![Active Echo Diagram](image)
Bench Testing and In Vivo Validation

Arbitrary Pattern Injection

- With one single active element, we are able to inject patterns to the B-mode image by creating a properly encoded ultrasound field.
- This feature enables many potential applications, some are beyond the tool tracking and guidance.
- Application example: Interventional HIFU element identification
Beam-forming “JHU”

A better use!
A better use!

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### Prostate-Specific Membrane Antigen-Targeted Photoacoustic Imaging for Prostate Cancer

#### Medical Intervention
- Ablative Therapy
- Biopsy Guidance
- Prostate Cancer Imaging
- Robotic Prostatectomy
- Partial Nephrectomy

#### Advanced US Imaging
- Elasticity Imaging
- Thermal Imaging
- Photoacoustic Imaging
- HIFU
- Computer Vision
- Robotics/Tracking/Sensorless

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#### Prostate-Specific Membrane Antigen-Targeted Photoacoustic Imaging for Prostate Cancer

Intensity of PA signal: $PA(\lambda) = \Gamma \Phi \mu_a(\lambda) = \Gamma \Phi \varepsilon(\lambda)$

- $\Gamma$: Grüniesen constant
- $\Phi$: laser fluence
- $\mu_a$: absorption coefficient
- $\varepsilon$: Extinction coefficient, known

$PA_{total} = PA_1 + PA_2 + \cdots + PA_M$

$[PA]_{M \times A} = [C]_{1 \times M}[S]_{M \times A}$

- $M$: number of wavelengths (measurement)
- $A$: number of absorbers

Min $\|PA - CS\|^2$

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Multispectral PA imaging + targeted contrast agent + spectral un-mixing algorithm

- Positive tumor after uptake of targeted agent
- Concentration map of endogenous absorber
- Concentration map of contrast agent
Prostate-Specific Membrane Antigen-Targeted Photoacoustic Imaging for Prostate Cancer

Ultrasound + Photoacoustic (PA) Imaging

- Pre-injection
- Post-injection: 2 hr
- Post-injection: 24 hr

Fluorescence (FL) Imaging

- Post-injection: 2 hr
- Post-injection: 24 hr

Three fluorescent-based PSMA-targeted dyes are evaluated:
- ICG $\rightarrow$ Dye I
- IRDye800CW $\rightarrow$ Dye II
- ATTO740 $\rightarrow$ Dye III
Back to prostate !!

Baseline (VSD+, PTZ-)

Seizure (VSD+, PTZ+)

Need for nerve guidance during peeling out procedure of fascia
**Proposed nerve-guided robot-assisted laparoscopic prostatectomy**

Step 1: Robotic tool approach through the ports on the abdominal incisions,

Step 2: Direct VSD staining of a prostate tissue through the abdominal incision port,

Step 3: Flushing out of the VSD on the prostate surface which is not bound at tissue membrane,

Step 4: Stimulation on nerves in the surgical region-of-interest, and

Step 5: Nerve-sparing prostatectomy with the augmented nerve map

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**Available time for VSD staining**

- Dissection of colon adhesions ~0:31
- Posterior approach with dissection of the seminal vesicles ~2:57
- Dissection of the anterior abdominal wall~10:50
- Opening of the endopelvic fascia and dissection of the periprostatic fat
- Suture of the dorsal venous complex
- Preservation of neurovascular bundles during left sided dissection
- Dissection of the left posterior pedicle ~33:20
- Apical and urethral dissection ~49:01
- Evaluation of nerve sparing with the ProPep electrodes ~54:14
- Vesicourethral anastomosis ~55:12
- Surgery ended ~1:07

Time point completing exposure of prostate capsuled with periprostatic fascia ~6-10 min
**In vivo experimental protocol**

**Pre-stimulation**
- **Voltage:** Electrical pulses
- **Time:** 5 ms

**Electrical Stimulation**
- **Time:** 62.5 ms

**Post-stimulation**
- **Time:** 1 min

**Fluorescence recording**
- **Exposure:** 500 ms
- **Frames per second:** ~2 fps

**Direct VSD administration**
- **Solution:** 1 mM R780 solution with DMSO and Cremaphor
- **Solution:** Saline solution

**Flush with saline solution**
- **Time:** 5 min

**Stimulating voltage**
- **Voltage:** 4V

**Stimulating time**
- **Time:** 1 min

**Fluorescence recording**
- **Time:** 3 min

**In vivo experimental setup**

**FL imaging module**
- **Camera:** sCMOS camera
- **Stimulator:** Electrical stimulator
- **ICP validation module:** ICP measurement system

**Stimulating module**
- **Stimulating source:** CW laser (780 nm)

**Stimulating probe**
- **Endoscopic probe**
- **Cannula**

**ICP variables**
- **Pr:** prostate
- **Pn:** penis
- **RCN:** right cavernous nerve
- **RCC:** right corpus cavernosum
- **ICP:** intracavernos pressure
Preliminary *in vivo* results on nerve localization on rat prostate:

(A) White light and FL images;
(B) Evolution of FL intensity during stimulation. The gradual decrease is due to photo-bleaching;
(C) Subtracted images between indicators, and its fusion on FL images.

Thank you!

Follow-up:
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Lab Homepage:
https://musiic.lcsr.jhu.edu

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