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

Emad M. Boctor, Ph.D.
Director of the Medical Ultrasound Imaging and Intervention Collaboration (MUSiiC) Research Laboratory

Jin Kang, Marty Pomper, Russ Taylor, Dean Wong, Arman Rahmim (UBC), Brad Wood (NIH), Les Loew (UConn)
Lei Chen, Bo Meng, Behnoosh Tavakoli, Jeeun Kang, Chloe Audigier, Ying Chen, Emran Anas
Alexis Cheng, Kai Zhang, Xiaoyu Guo, Hyun-Jae Kang, Younsu Kim, Fereshteh Aalamifar

1

Disclaimer

- Emad M. Boctor is a co-founder of Clear Guide Medical, Sonavex, and DolphinMedical. The terms of this arrangement are being managed by the Johns Hopkins University in accordance with its conflict of interest policies
- Under a licensing agreement between Acoustic Medsystems, Intuitive Surgery, Cook Medical, Siemens and the Johns Hopkins University, Dr. Boctor is entitled to royalties on a different invention. This arrangement has been reviewed and approved by the Johns Hopkins University in accordance with its conflict of interest policies

2

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

Medical Intervention	Research Thrusts
• Ablative Therapy • Biopsy Guidance • External Beam Radiation Therapy • Robotic Prostatectomy • Partial Nephrectomy	• Advanced Ultrasound Imaging (Photoacoustic, Thermal, and Elasticity) • Co-Robotic Ultrasound Imaging • Ultrasonically Smart Tools (smart catheter, needles, and probe) • Ultrasound for Stimulation and Treatment

3

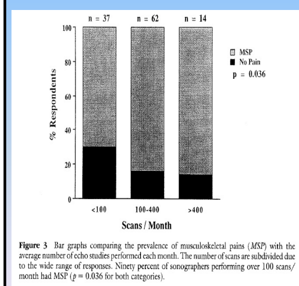
Medical UltraSound for Imaging and Intervention Collaboration (MUSiiC) Research Laboratory

Medical Intervention	Research Thrusts
• Ablative Therapy • Biopsy Guidance • External Beam Radiation Therapy • Robotic Prostatectomy • Partial Nephrectomy	• Advanced Ultrasound Imaging (Photoacoustic, Thermal, and Elasticity) • Co-Robotic Ultrasound Imaging • Ultrasonically Smart Tools (smart catheter, needles, and probe) • Ultrasound for Stimulation and Treatment

4

Co-robotic Ultrasound Imaging

Wrist flexion and “pinch” grip | Trunk and neck twist | Trunk flexion



Challenges on ultrasound imaging:

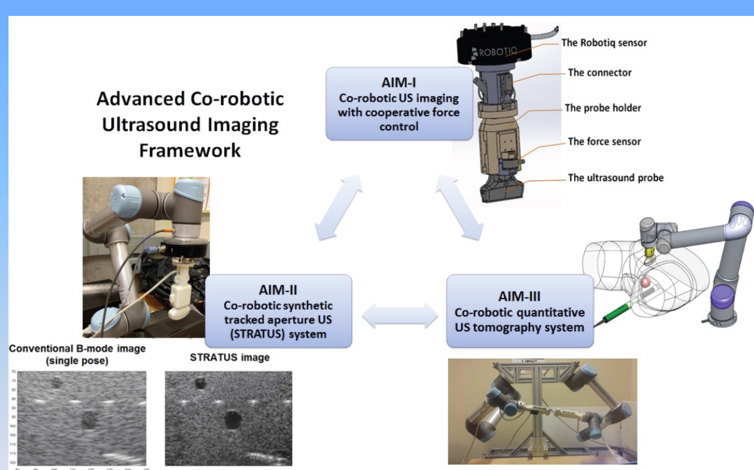
- Limited image quality and field of view
- Limited reproducibility
- High user dependency
- Work related musculoskeletal pain (MSP) affect 63 - 91% of sonographers

Robotic Ultrasound Solution

Smith A. C., et al., J Am Soc Echocardiog, 1997.
Coffin C., Reports in Medical Imaging, 2014.

5

Co-robotic Ultrasound Imaging



6

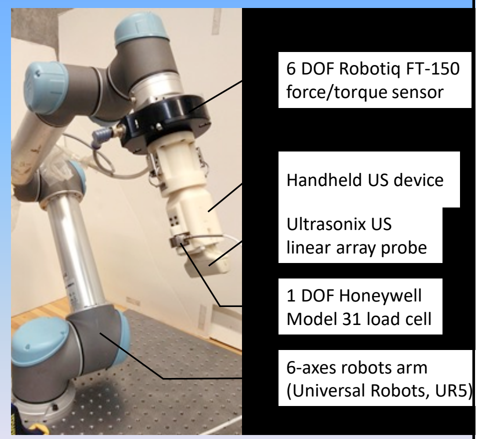
Co-robotic Ultrasound Imaging

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

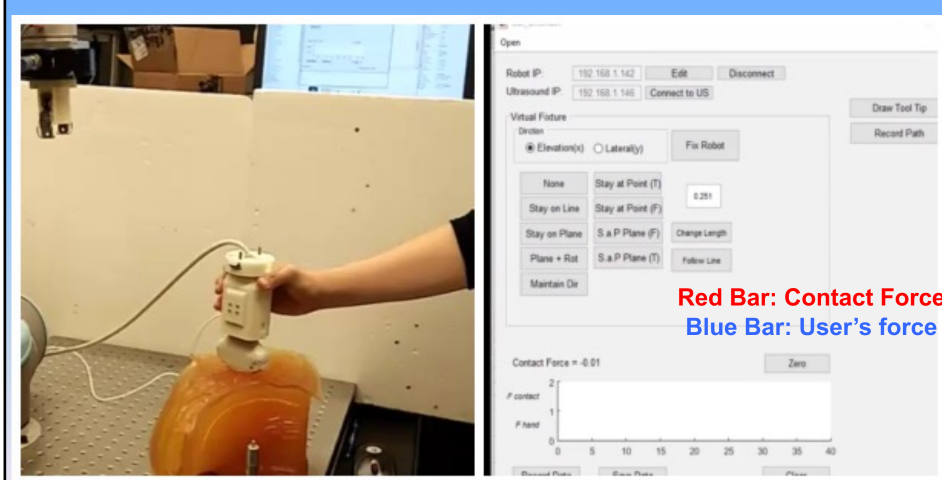
The proposed co-robotic system is composed of:

- 6-axis robotic arm
- 6 DOF force/torque sensor
- Detachable handheld US device with 1 DOF load cell
- Ultrasound (US) probe



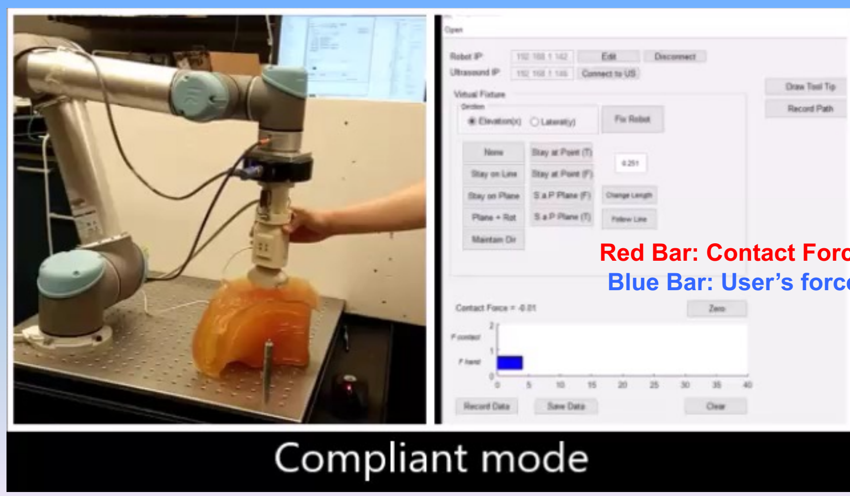
7

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



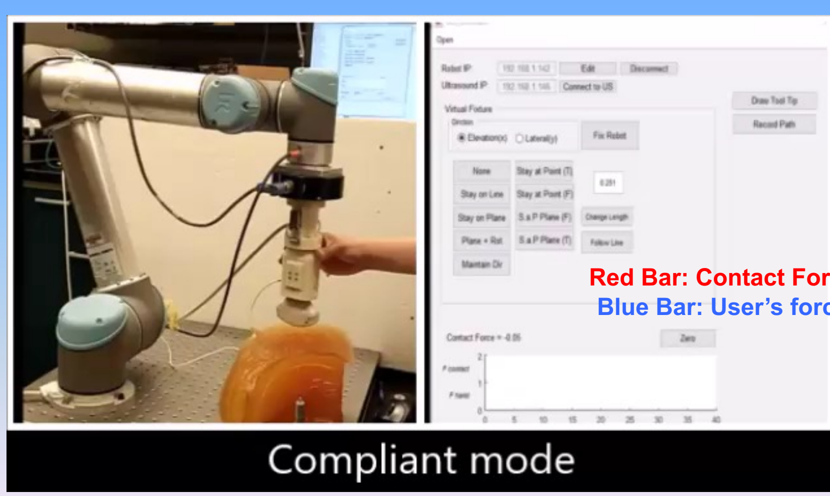
8

Co-robotic Ultrasound Imaging System demo – case 3 (Robotic)



9

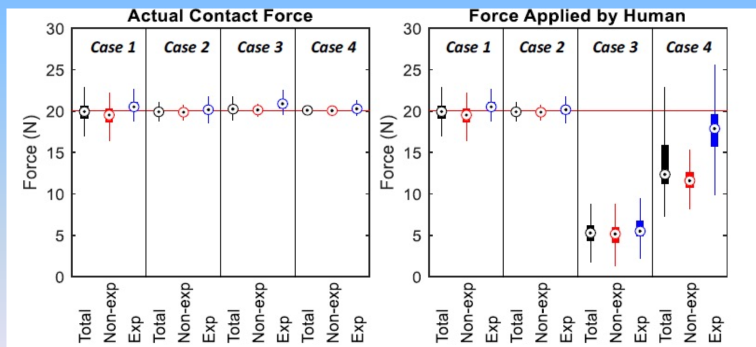
Co-robotic Ultrasound Imaging System demo – case 4 (Robotic w/ constraint)



10

Co-robotic Ultrasound Imaging
Result- Applied Force Reduction

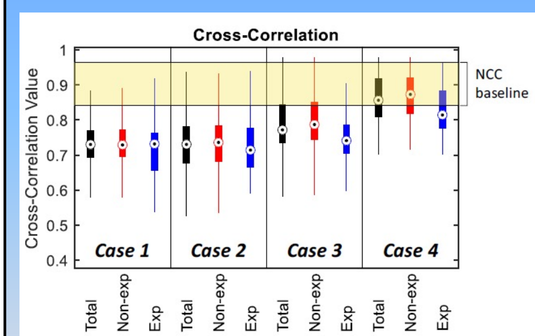
- The robot assistance in case 3 and case 4 reduces the force applied by the human participants from 20 N to an average of 5.48 N and 13.62 N, which are 73 % and 32 % reductions



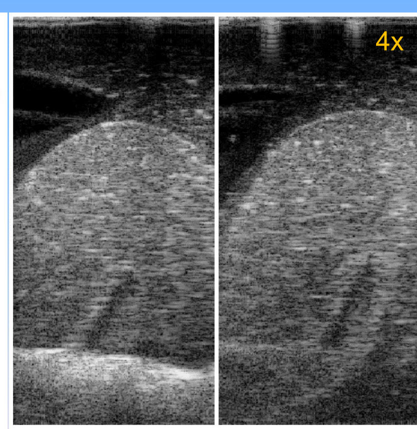
Case 1: Freehand scanning *Case 2*: Freehand scanning with contact force feedback
Case 3: Co-robotic scanning with no constraint *Case 4*: Co-robotic scanning with constraint

11

Co-robotic Ultrasound Imaging
Result- Stability of Ultrasound Images

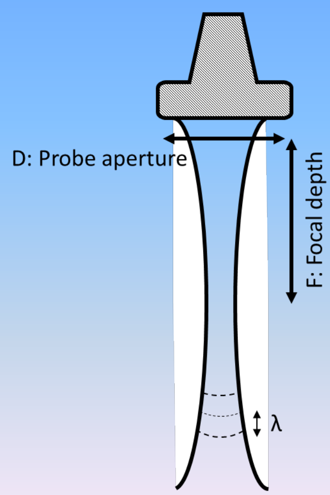


Case 1: Freehand scanning
Case 2: Freehand scanning with contact force feedback
Case 3: Co-robotic scanning with no constraint
Case 4: Co-robotic scanning with constraint



12

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



- Ultrasound image resolution is determined by focal depth (*F*), center frequency (*1/λ*), 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.

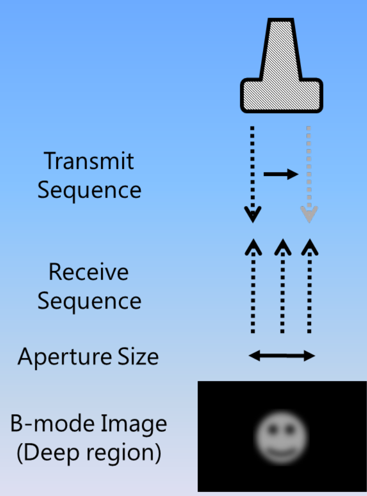
$$p(x) = p_0 e^{-\alpha x} e^{-jw(t-x/c)}$$

Attenuation coefficient $\alpha \cong \frac{\alpha_0}{\lambda}$

- Probe aperture is the only parameter we can manage to increase if the region of interest is in deep region.

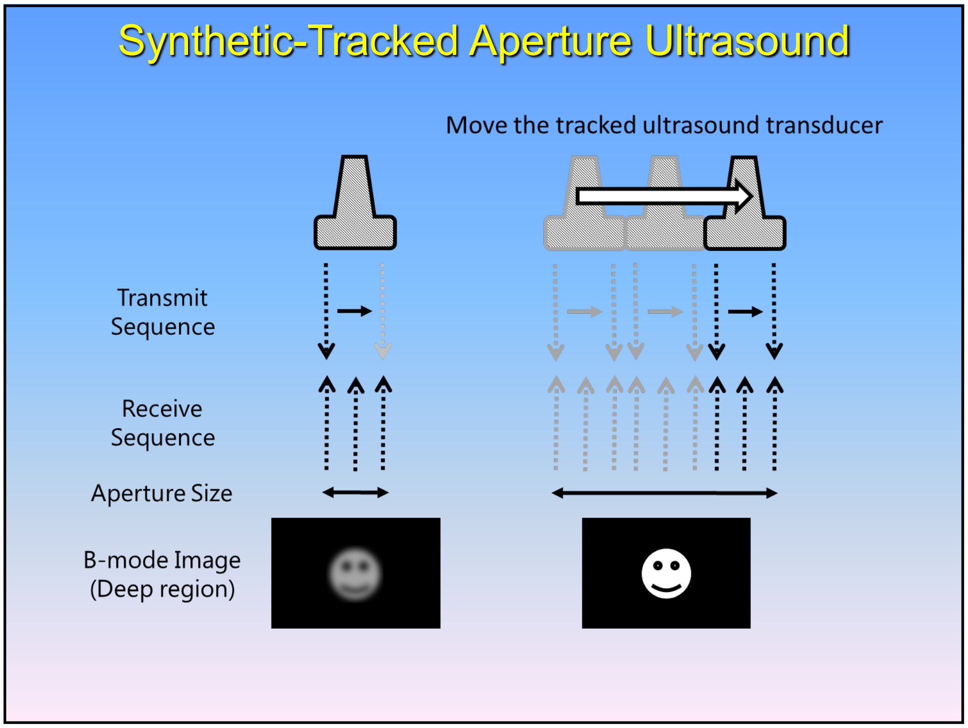
13

Synthetic Aperture

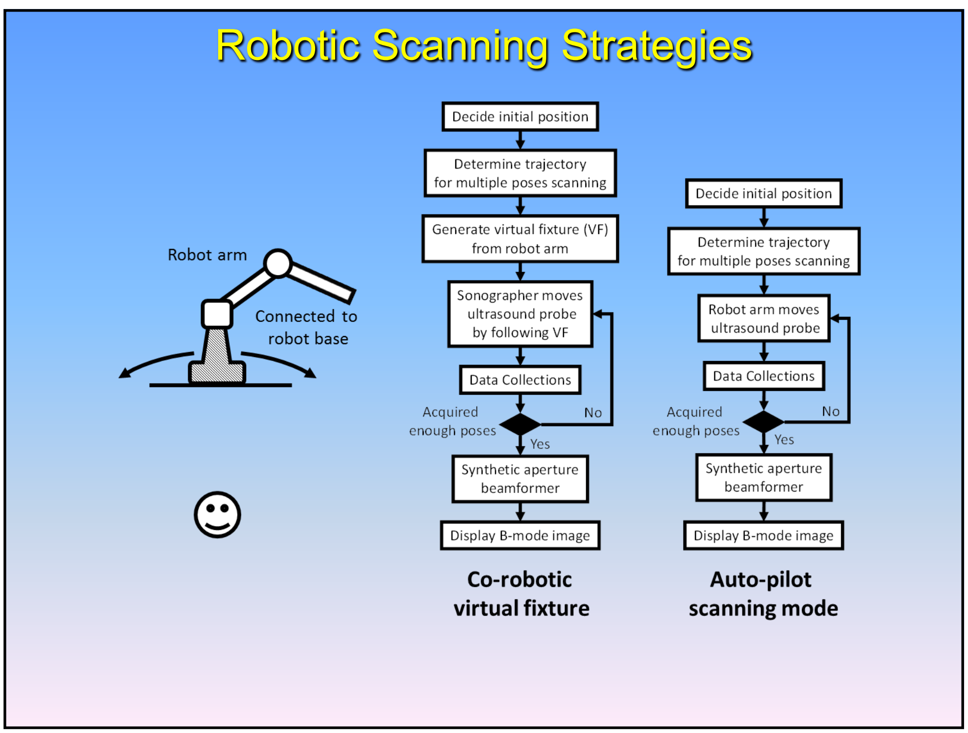


- Multiple sub-aperture will be synthesized to create a big aperture in transmission and receive.
- However, it is limited by the physical size of ultrasound transducer.

14

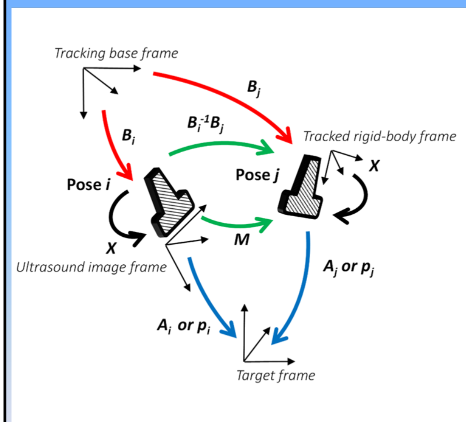

Synthetic-Tracked Aperture Ultrasound
Move the tracked ultrasound transducer
Transmit Sequence
Receive Sequence
Aperture Size
B-mode Image (Deep region)

15


Robotic Scanning Strategies
Robot arm
Connected to robot base
Decide initial position
Determine trajectory for multiple poses scanning
Generate virtual fixture (VF) from robot arm
Sonographer moves ultrasound probe by following VF
Data Collections
Acquired enough poses
No
Yes
Synthetic aperture beamformer
Display B-mode image
Co-robotic virtual fixture
Decide initial position
Determine trajectory for multiple poses scanning
Robot arm moves ultrasound probe
Data Collections
Acquired enough poses
No
Yes
Synthetic aperture beamformer
Display B-mode image
Auto-pilot scanning mode

16

Coordinate Systems and Motion Determination



Robot base to US image frame

1. *B*: Robot base to robot end-effector
2. *X*: Robot end-effector to US image frame

Definition of motion

$$M = X^{-1}B_i^{-1}B_jX$$

Motion to move from pose *i* to *j*

$$B_j = B_i\, XMX^{-1}$$

Translational Motion

$$B_j = B_i\, X\begin{bmatrix} I & t_M \\ 0_{1\times3} & 1 \end{bmatrix}X^{-1}$$

$$= \begin{bmatrix} R_{B_i} & R_{B_i}R_Xt_M + t_{B_j} \\ 0_{1\times3} & 1 \end{bmatrix}$$

17

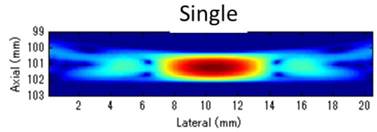
Field II Simulation

- 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.

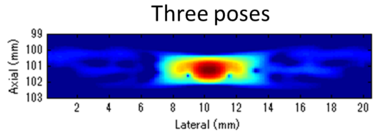
Definition of motion

$$M = X^{-1}B_j^{-1}B_iX$$

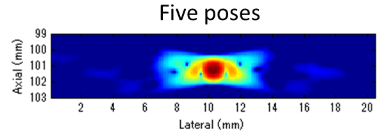
Single



Three poses



Five poses



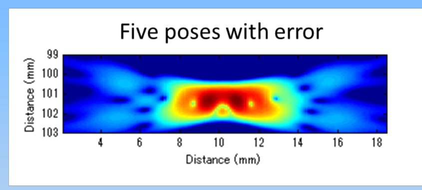
J.A. Jensen and N. B. Svendsen, "Calculation of pressure fields from arbitrarily shaped, apodized, and excited ultrasound transducers", *IEEE Trans. Ultrason., Ferroelec., Freq. Contr.*, 39, pp. 262-267, 1992.

18

Five poses with error

Simulation of error for a motion

$$\hat{M} = X^{-1}\Delta X^{-1}B_j^{-1}\Delta B_j^{-1}B_i\Delta B_i X\Delta X$$



- 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.

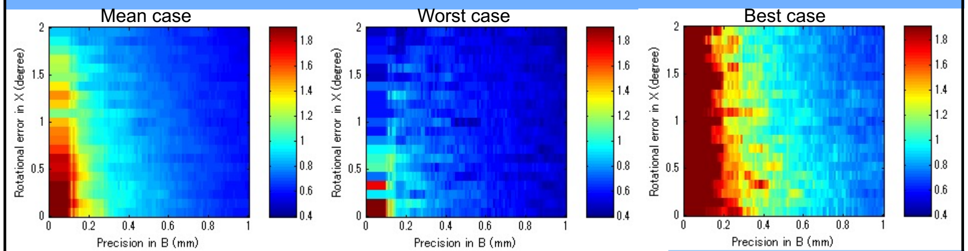
19

Image Quality Analysis

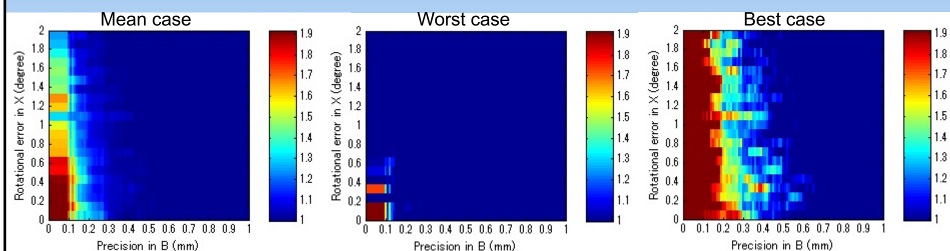
- We quantitatively evaluated the ultrasound image quality while introducing error in tracking sensor (ΔB) and ultrasound calibration (ΔX).
- The size of the point spread function is measured by counting the number of pixels over a certain threshold (-25 dB).
- The single pose result was set as the baseline (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 Xs are computed, and Mean, Worst, and Best case are shown.

20

Image Quality Analysis



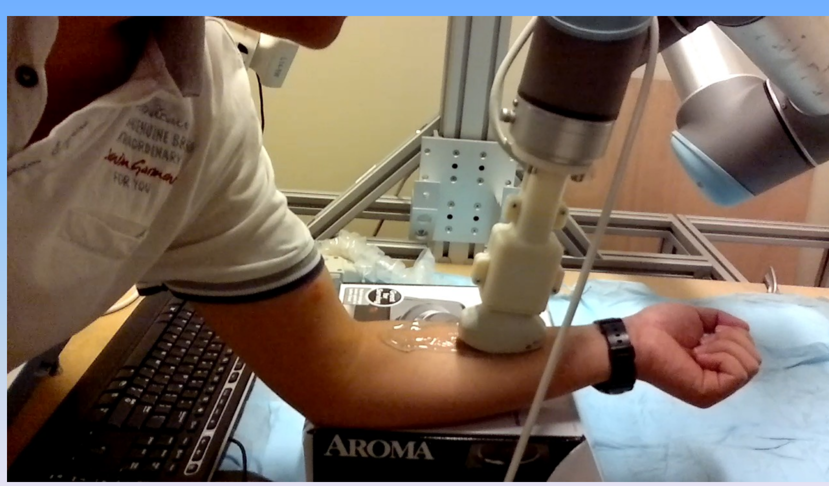
Improvement of pixel compared to single pose



Improvement of pixel compared to single pose (normalized)

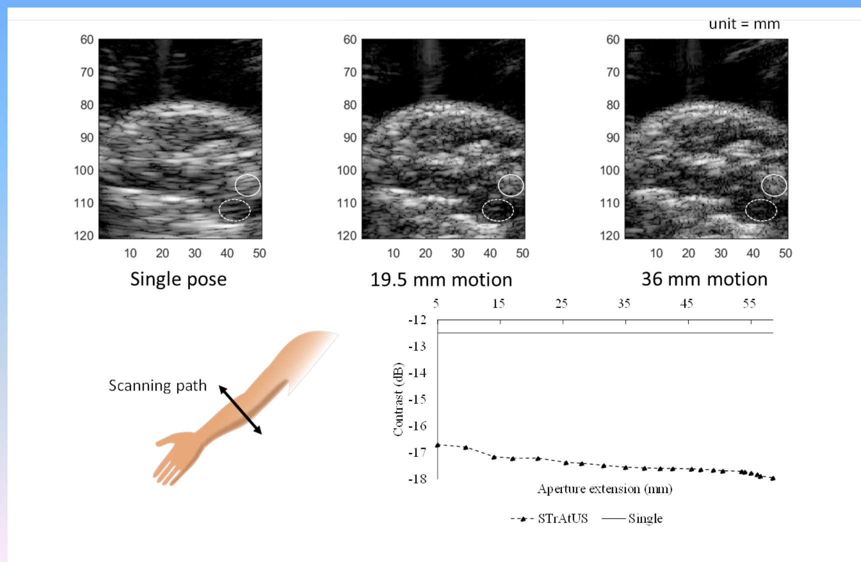
21

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



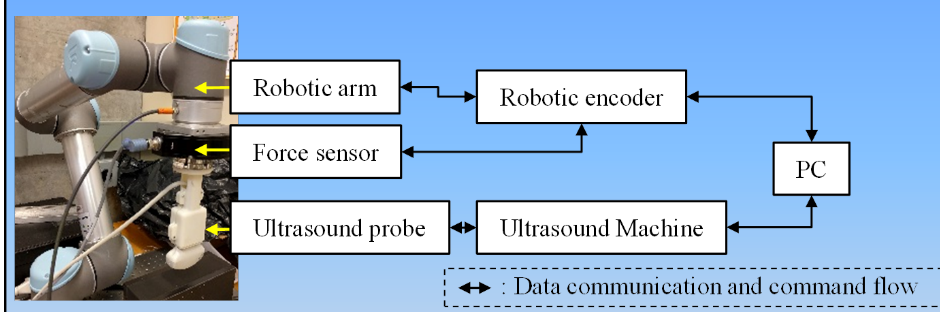
22

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



23

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.

24

Co-Robot Control:
Constrained Optimization Approach

What is Virtual Fixture?

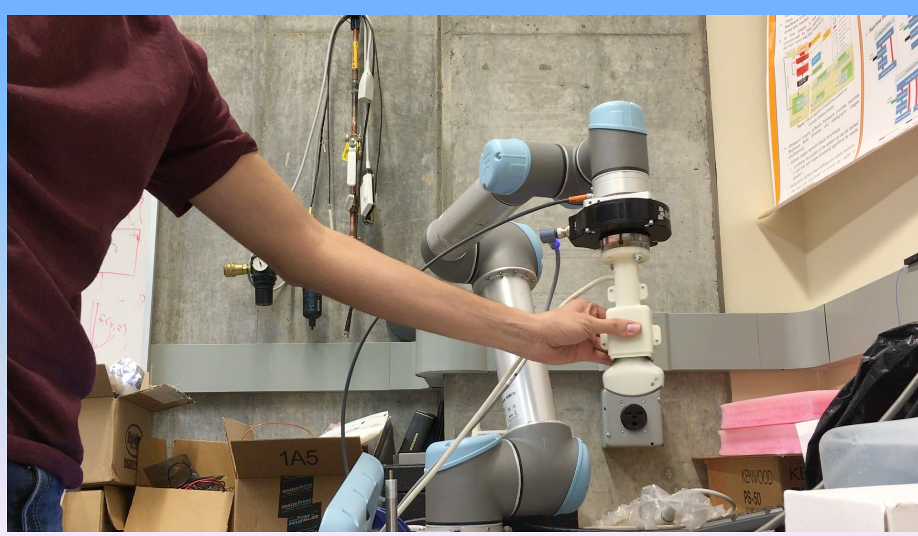
- Virtual fixture is a concept of creating a physical restriction on the motion by constraining the robotic control.

Virtual Fixture Scenarios

1. Stay on a line
2. Stay on a plane
3. Stay on a plane (1DOF rotation)
4. Keep contact force

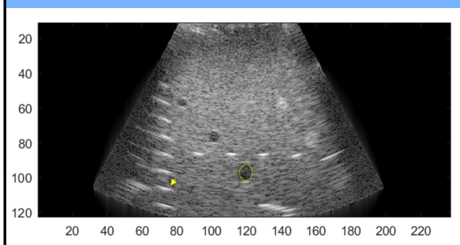
25

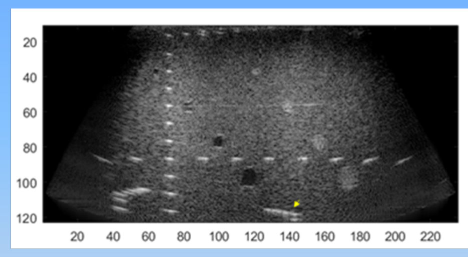
Co-Robot Control:
Constrained Optimization Approach



26

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



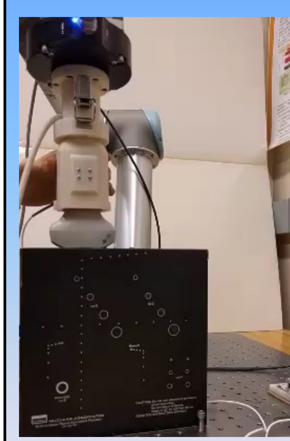


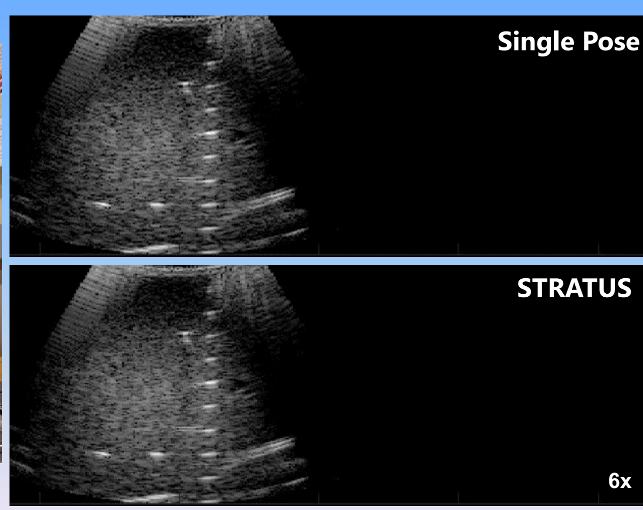
Left: Single pose B-mode ultrasound image of general US phantom.
Right: STRATUS images synthesized in the range of 60 mm motion data; field-of-view expanded by 65.5 mm.

	Single	STRATUS: 60 mm
FWHM (mm)	3.87	2.37
Contrast (dB)	-7.14	-10.67
SNR (dB)	25.01	29.35

27

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

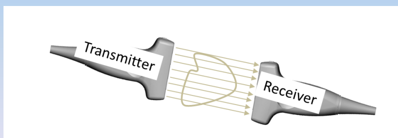




28

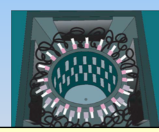
Quantitative Ultrasound Imaging: Ultrasound Tomography

- 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.



Softvue

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


A Ring transducer

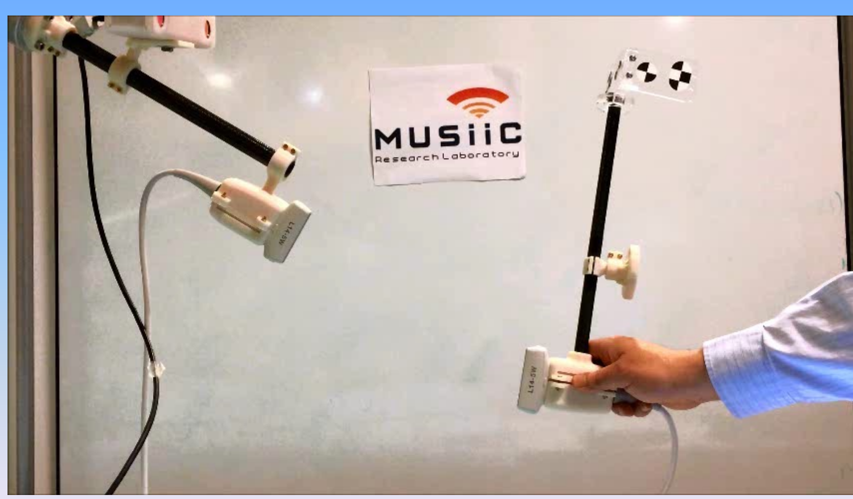
R W Prager, et al. "Three Dimensional Ultrasound Imaging" *Journal of Eng. In Medicine, 2009.*


Tomographic image

Li *et al*, An improved automatic TOF picker for US tomography, 2009.

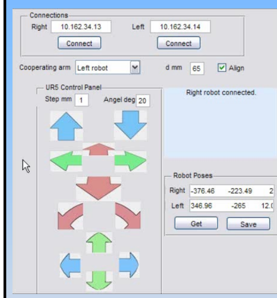
29

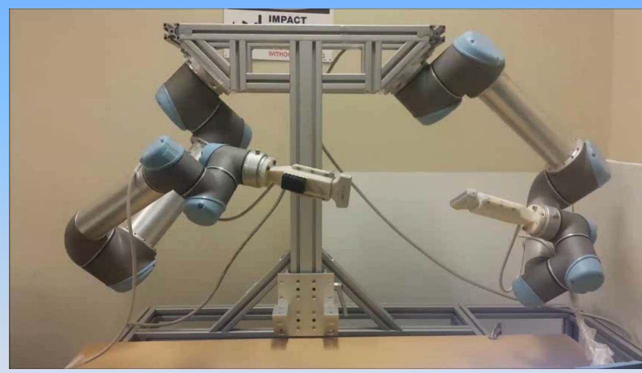
Co-robotic Ultrasound Tomography: First Prototype



30

Co-robotic Ultrasound Tomography: Second Prototype

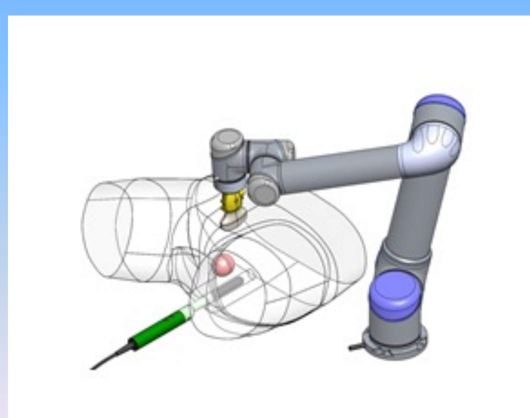




31

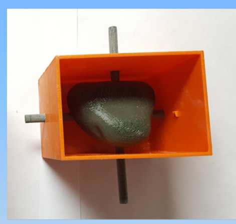
Co-robotic Ultrasound Tomography: Prostate Cancer

Fereshteh Aalamifar, Reza Seifabadi, Peter Choyke, Maria Merino, Peter Pinto, Arman Rahmim, Bradford J. Wood, Emad M. Boctor

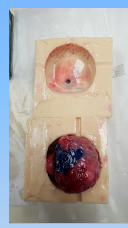


32

Co-robotic Ultrasound Tomography: Prostate Cancer



Mold for patient specific US friendly phantom

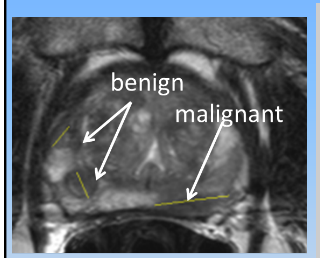


US friendly phantom containing prostate

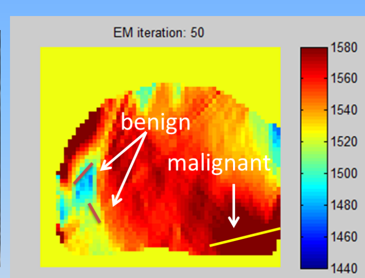
Scanning the ex-vivo prostate

33

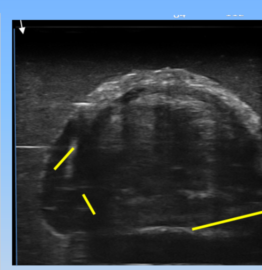
Co-robotic Ultrasound Tomography: Prostate Cancer: Initial Results



MRI image



Tomographic image



B-mode image

34

Co-robotic Ultrasound Catheter Tracking

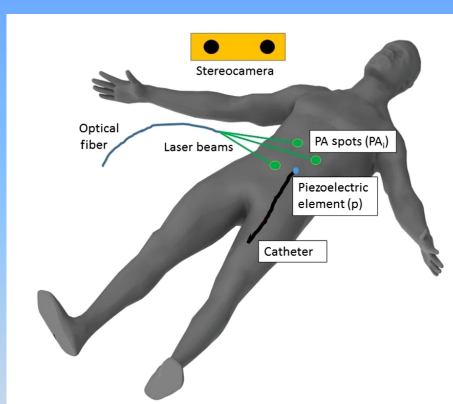
A New Robotic Ultrasound System for Tracking
a Catheter with an Active Piezoelectric Element

Qianli Ma, Joshua Davis, Alexis Cheng, Gregory Chirikjian, Emad Boctor

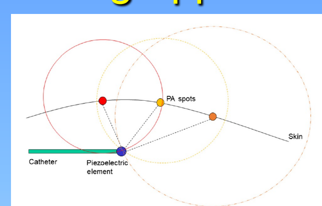
Laboratory for Computational Sensing and Robotics
The Johns Hopkins University

35

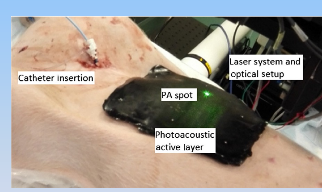
Co-robotic Ultrasound Catheter Tracking: Photoacoustic Remote Tracking Approach



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.



Graphical description of PZT element localization.



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 Itsarachaiyot, Haichong K. Zhang, Clifford R. Weiss, Russell H. Taylor, Emad M. Boctor, "Photoacoustic-based catheter tracking: simulation, phantom, and in vivo studies," J. Med. Imag. 5(2) 021223 (27 March 2018)

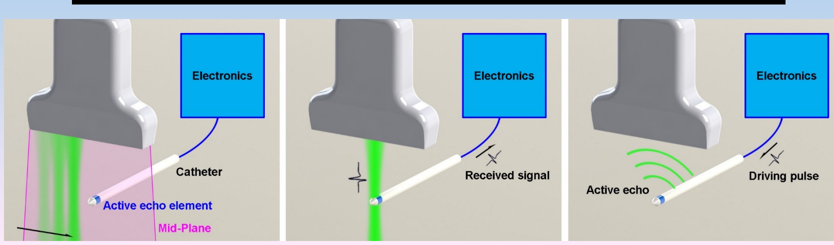
36

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

Medical Intervention	Research Thrusts
• Ablative Therapy • Biopsy Guidance • External Beam Radiation Therapy • Robotic Prostatectomy • Partial Nephrectomy	• Advanced Ultrasound Imaging (Photoacoustic, Thermal, and Elasticity) • Co-Robotic Ultrasound Imaging • Ultrasonically Smart Tools (smart catheter, needles, and probe) • Ultrasound for Stimulation and Treatment

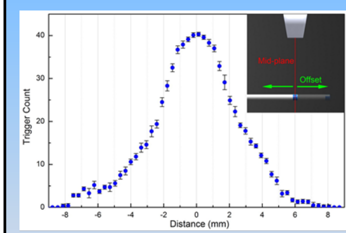
37

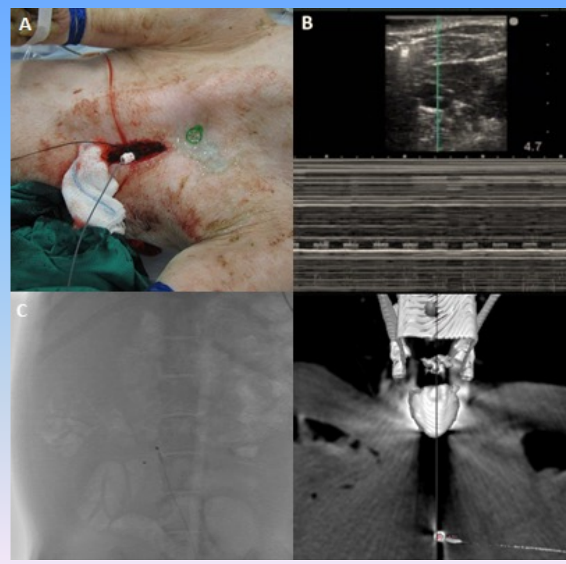
Active Echo



38

Bench Testing and In Vivo Validation

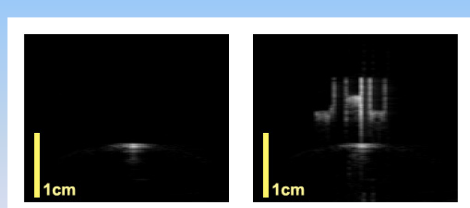


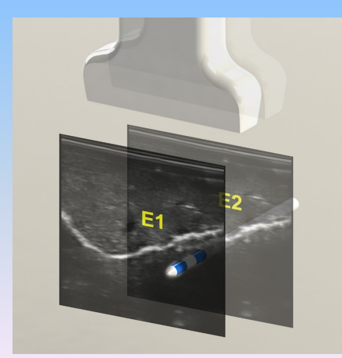


39

Arbitrary Pattern Injection

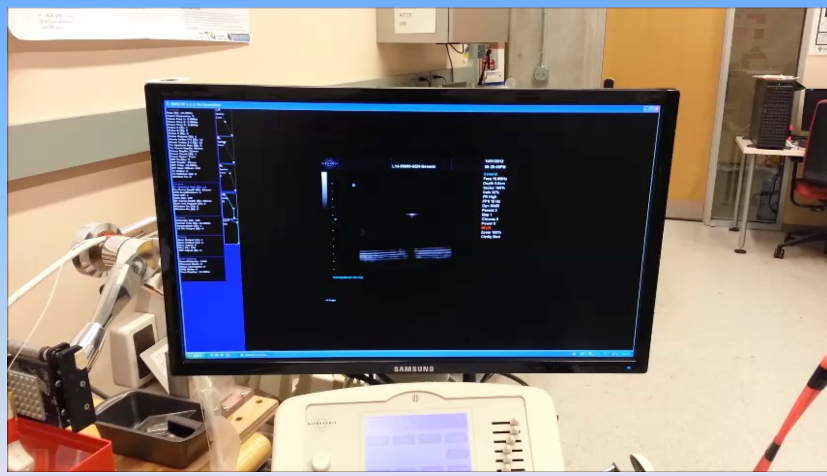
- With one single active element, we are able to inject patterns to the B-mode image by creating a properly encoded ultrasound field.
- This feature enables many potential applications, some are beyond the tool tracking and guidance.
- Application example: Interventional HIFU element identification





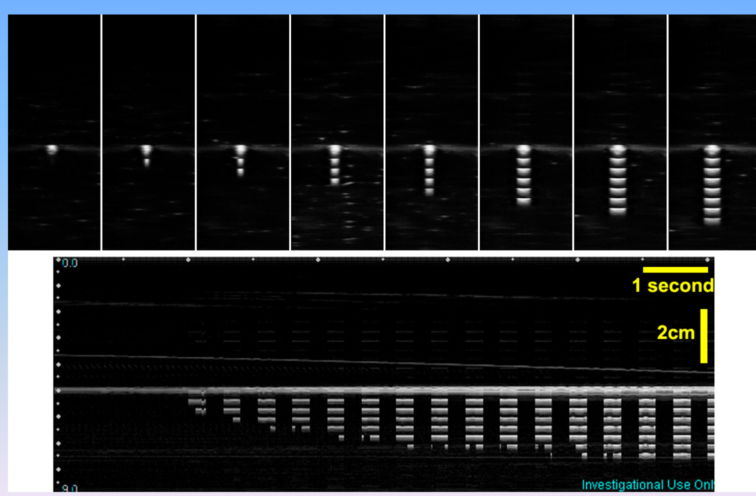
40

Beam-forming "JHU"



41

A better use!



42

A better use!

43

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

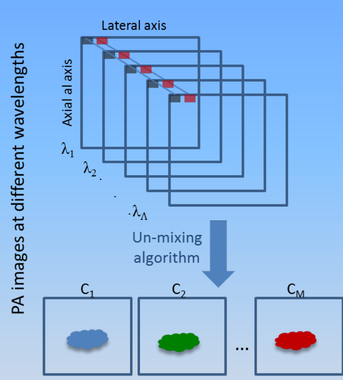
44

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

Medical Intervention	Advanced US Imaging
• Ablative Therapy	• Elasticity Imaging
• Biopsy Guidance	• Thermal Imaging
• Prostate Cancer Imaging	• Photoacoustic Imaging
• Robotic Prostatectomy	• HIFU
• Partial Nephrectomy	• Computer Vision
	• Robotics/Tracking/Sensorless

45

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



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

Γ: Gruneisen constant

Φ: laser fluence

μ_a : absorption coefficient

C: Concentration of absorber, unknown variable

ε: Extinction coefficient, known

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

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

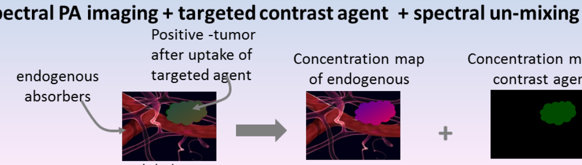
number of wavelengths (measurement)

number of absorbers

PA reference spectrum

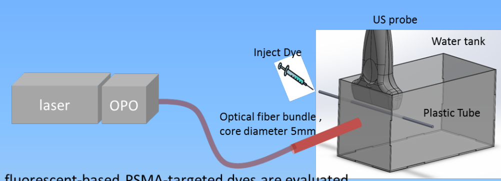
$$\text{Min } \|PA - CS\|^2$$

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

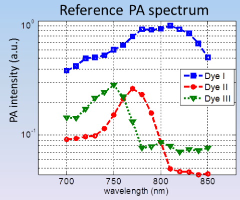


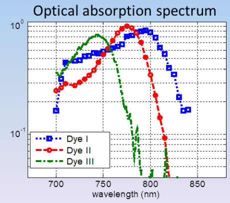
46

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

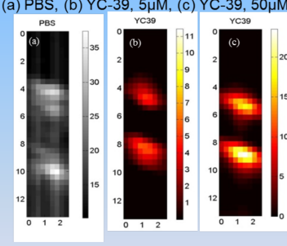


Three fluorescent-based PSMA-targeted dyes are evaluated
- ICG →Dye I
- IRDye800CW →Dye II
- ATTO740 →Dye III





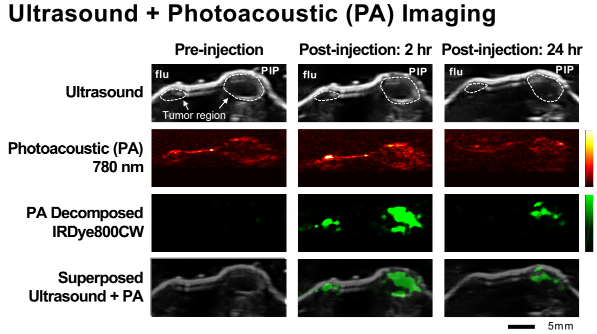
(a) PBS, (b) YC-39, 5μM, (c) YC-39, 50μM



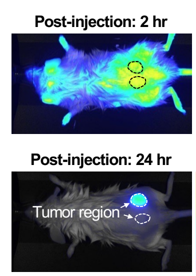
47

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

Ultrasound + Photoacoustic (PA) Imaging

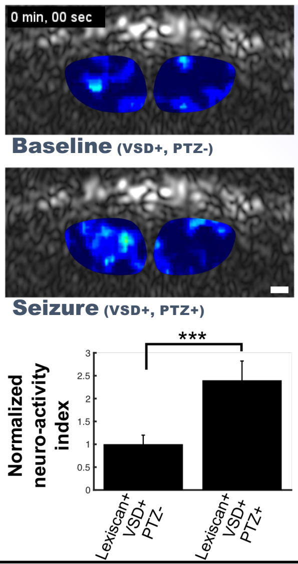


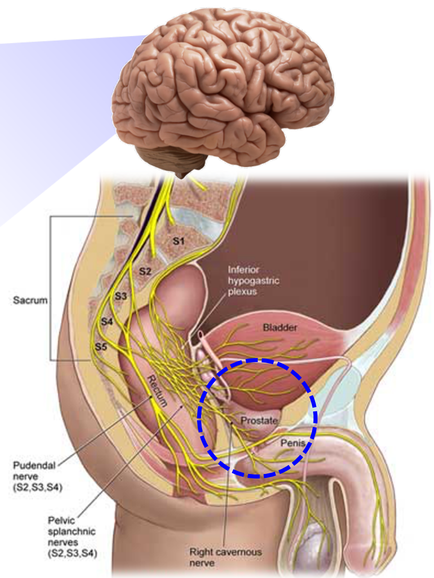
Fluorescence (FL) Imaging



48

Back to prostate !!

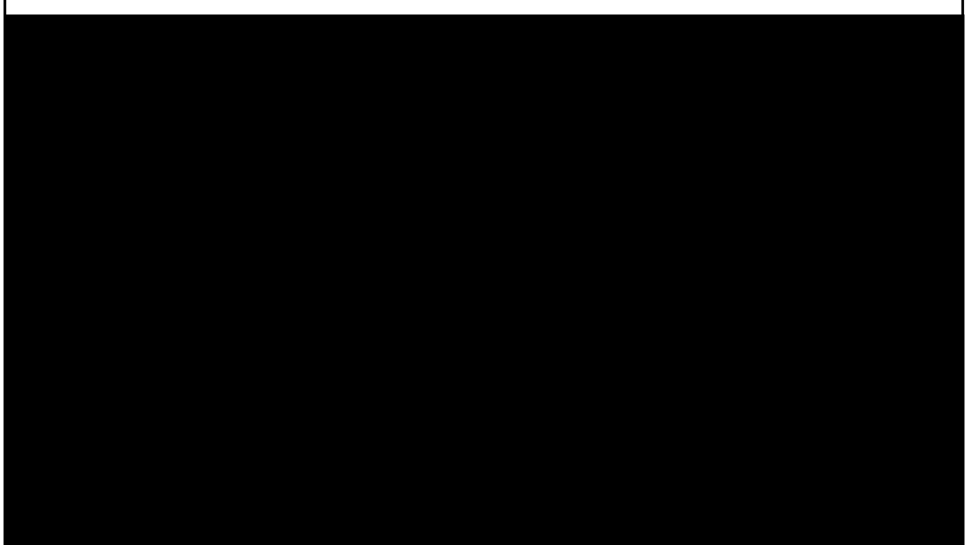




49

49

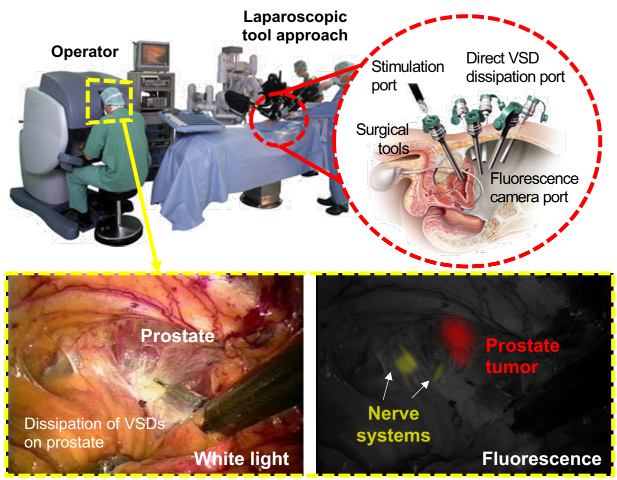
Need for nerve guidance during peeling out procedure of fascia



50

50

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

51

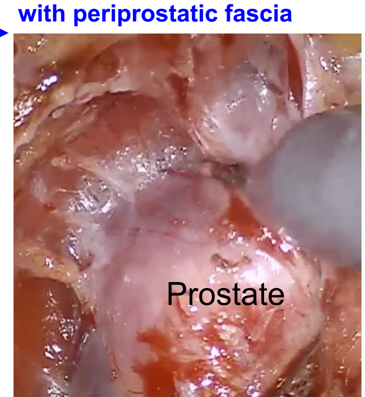
51

Available time for VSD staining

- Dissection of colon adhesions ~0:31
- Posterior approach with dissection of the seminal vesicles ~2:47
- 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

8-10 min

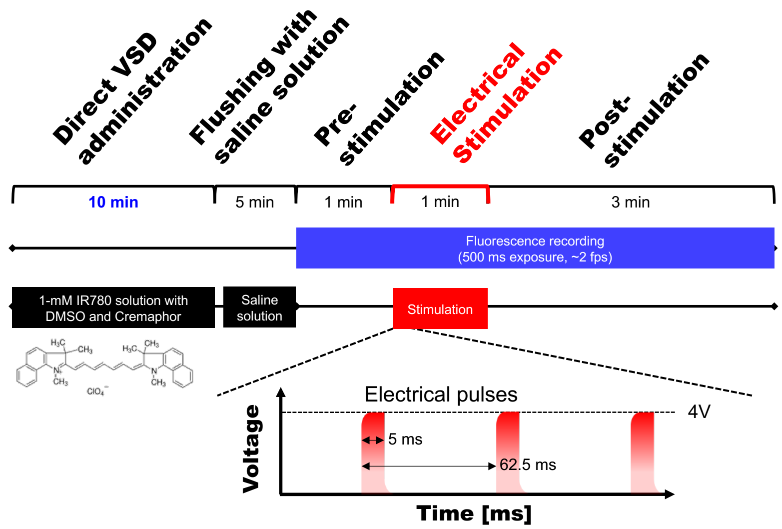
Time point completing exposure of prostate capsuled with periprostatic fascia



52

52

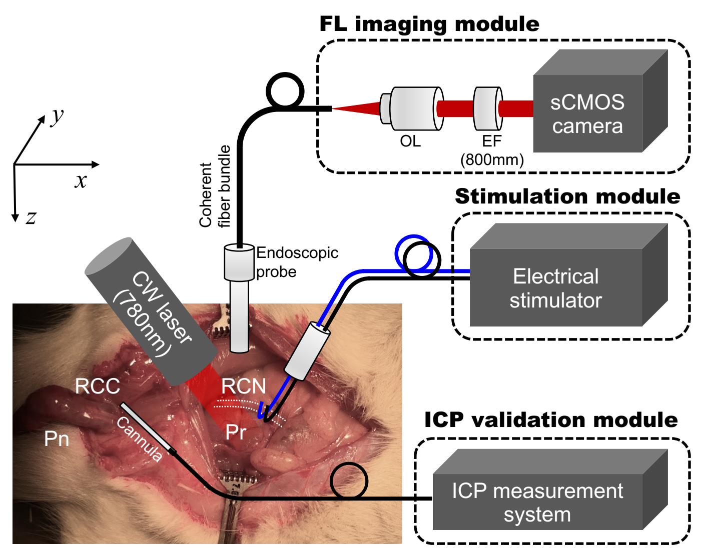
In vivo experimental protocol



53

53

In vivo experimental setup

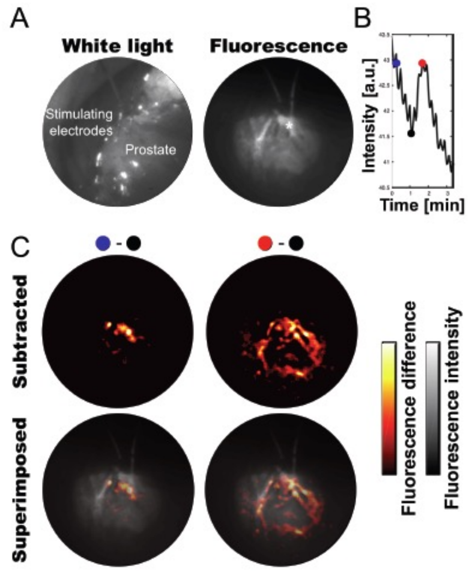


Pr: prostate; Pn: penis; RCN: right cavernous nerve; RCC: right corpus cavernosum
ICP: intracavernos pressure

54

54

Go back to prostate !!



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.

55

Thank you !

Follow-up:
Emad Boctor
eboctor@jhmi.edu

Lab Homepage:
https://musiic.lcsr.jhu.edu

Funding Acknowledgment

NIH (Active): R24MH106083, 1R21CA202199, B2B, R01HL139543, 1R01EB021396, R44CA192482
NSF (Active): CAREER 1653322, NRI
CDMRP (Active): Postdoc fellowship PCRP
Industry and State of MD: Intuitive Surgery Research Grant, MII phase II
Hopkins Internal Grants: Discovery Award, ATIP, Coulter Foundation, Cohen

MUSiiC Research Laboratory | Laboratory for Computational Sensing + Robotics, The Johns Hopkins University | ERC | CISST | JOHNS HOPKINS UNIVERSITY

61