Real-Time Telerobotic 3D Ultrasound for Soft-Tissue Guidance Concurrent with Beam Delivery

Dimitre Hristov
Radiation Oncology
Stanford University

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The team

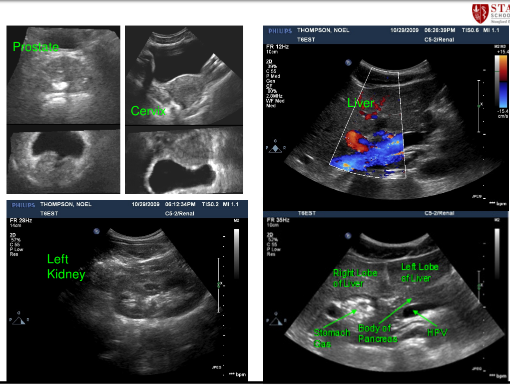
- **Stanford Radiation Oncology**
  - Can Kirmizibayrak
- **Stanford Bio-robotics**
  - Ken Salisbury
  - Jeff Schlosser
- **Philips Ultrasound Investigations**
  - Vijay Shamdasani
  - Steven Metz

Disclosure: Dimitre Hristov is a recipient of pass-through royalties from technology licensed to Resonant Medical (Elekta) and research support from Philips.

The state of art in EBRT image-guidance

Add-on, real-time, **volumetric, soft-tissue** guidance during radiation beam delivery is unmet challenge

Ultrasound soft-tissue imaging



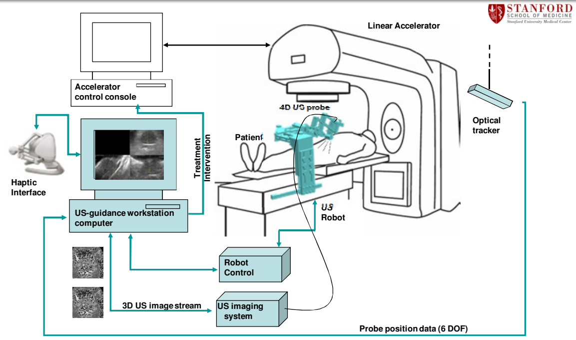
Previous work on US guidance

- A. Hsu, N. R. Miller, P. M. Evans et al., "Feasibility of using ultrasound for real-time tracking during radiotherapy," Medical physics 32 (6), 1500-1512 (2005).
- Q. Xu and R. J. Hamilton, "A novel respiratory detection method based on automated analysis of ultrasound diaphragm video," Medical physics 33 (4), 916-921 (2006).
- A. Sawada, K. Yoda, M. Kokubo et al., "A technique for noninvasive respiratory gated radiation treatment system based on a real time 3D ultrasound image correlation: a phantom study," Medical physics 31 (2), 245-250 (2004).
- F. Jacso, A. Kouznetsov, and W. L. Smith, "Development and evaluation of an ultrasound-guided tracking and gating system for hepatic radiotherapy," Med Phys 36 (12), 5633-5640 (2009).
- Bell MA, Byram BC, Harris EJ, Evans PM, Bamber JC. In vivo liver tracking with a high volume rate 4D ultrasound scanner and a 2D matrix array probe. Phys Med Biol. 2012 Mar 7;57(5):1359-74.

The tough questions

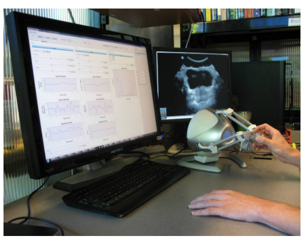
- **How to reliably acquire US images during beam delivery?**
- **How to accommodate telerobotic imaging in treatment designs?**
- **Is robust ultrasound monitoring/tracking of actual human anatomy feasible?**

Novel image guidance solution

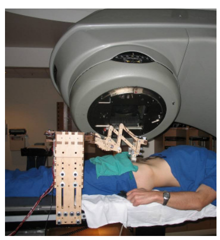


➡ ***Telerobotic system to enable remote probe control***

Telerobotic imaging



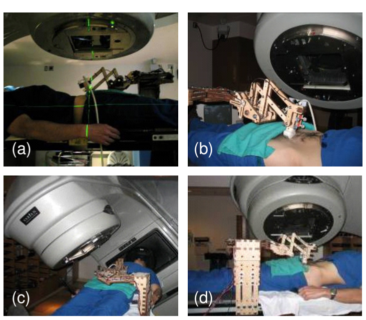
Remote Haptic Interface



Robot

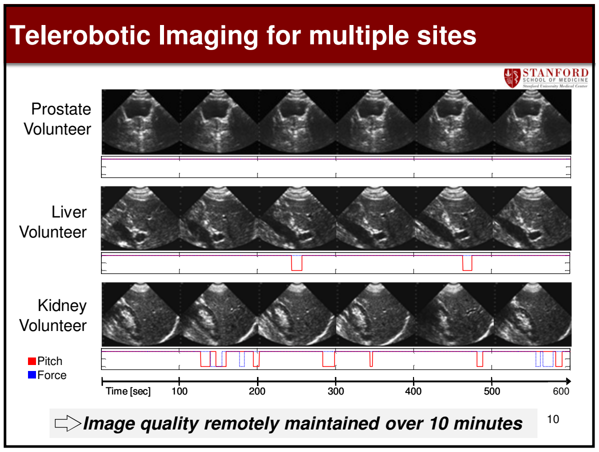
Schlosser J, Salisbury K, Hristov D, **Telerobotic system concept for real-time soft-tissue imaging during radiotherapy beam delivery**, Med Phys. 2010 Dec;37(12):6357-67.

Robot interference with the LINAC?



Compact design to avoids gantry collisions.

Schlosser J, Salisbury K, Hristov D, Med Phys. 2010 Dec;37(12):6357-67.


Telerobotic Imaging for multiple sites
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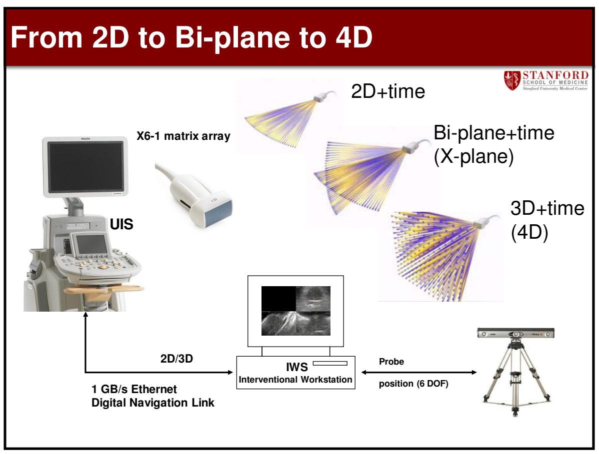
Prostate Volunteer
Liver Volunteer
Kidney Volunteer
Pitch
Force
Time [sec]
100
200
300
400
500
600
Image quality remotely maintained over 10 minutes
10


From 2D to Bi-plane to 4D
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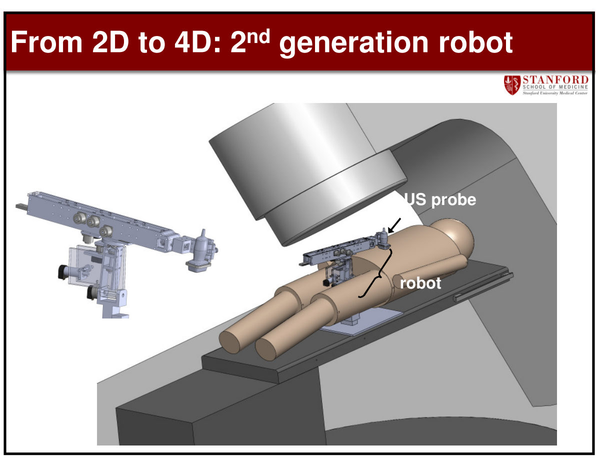
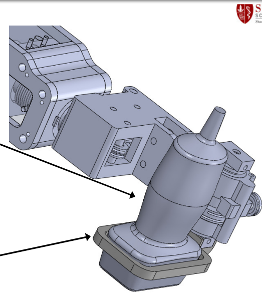
2D+time
X6-1 matrix array
Bi-plane+time
(X-plane)
UIS
3D+time
(4D)
2D/3D
IWS
Interventional Workstation
Probe
position (6 DOF)
1 GB/s Ethernet
Digital Navigation Link


From 2D to 4D: 2nd generation robot
STANFORD SCHOOL OF MEDICINE
US probe
robot

From 2D to 4D: 2nd generation robot

Large portion of probe is available for operator to grip by hand

Probe quickly snaps in and out for easy replacement with "dummy" probe during CT



The tough questions

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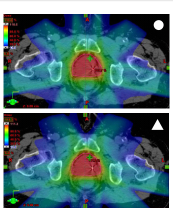
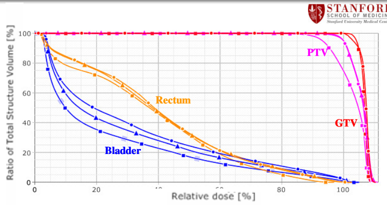
Treatment Plan Impact

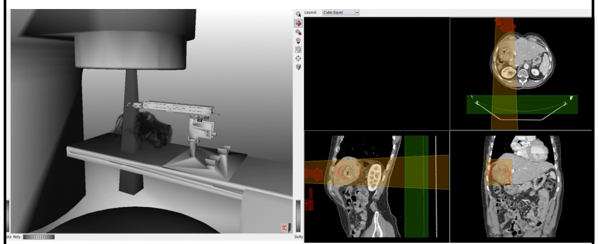




● Clinical prostate IMRT plan
▲ Re-optimized IMRT plan with restricted beam angles to avoid US probe and robot links
■ Re-optimized plan with 2mm margin reduction as potentially enabled by real-time image guidance

Plans are nearly identical. Potential margin reduction from real-time guidance is beneficial.

Treatment impact: evaluation tool



Simulation environment incorporating exact Linac, patient, robot 3D models

The tough questions

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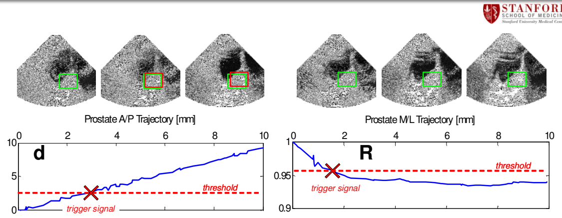
Online Internal Displacement Monitoring



Tissue Displacement Parameters **(TDP):**
d - in-plane displacement
R - max correlation value

Trigger signal is activated if a TDP exceeds threshold.

J Schlosser, K Salisbury, D Hristov,
Online Image-based Monitoring of Soft-tissue Displacements for Radiation Therapy of the Prostate, IJROBP, 3(5), 08/2012

Motion Detection: Experimental Evaluations

- Trans-abdominal robotic prostate imaging in 5 volunteers for ~ 12 minutes at different probe pressure levels
  - Determine TDP inter- and intra- subject variability over 20 second periods
  - Establish TDP thresholds for acceptable false positive rates across all subjects

J Schlosser, K Salisbury, D Hristov,
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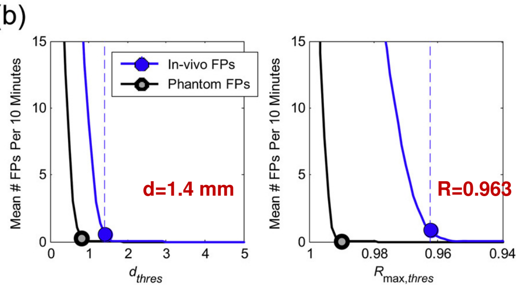
Selection of TDP threshold values

(b)

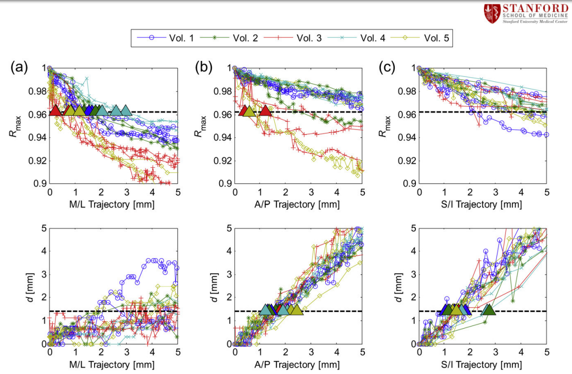


~1 False Positive per 7 min

Motion Detection: Experimental Evaluations

- Simulate prostate displacements by manually moving the tracked probe with respect to prostate
  - Evaluate detected displacements at the TDP thresholds
  - Determine range of detected displacements at TDP thresholds

TDP sensitivity to in-vivo displacements



TDP sensitivity to in-vivo displacements

For TDP thresholds of d=1.4 mm and R=0.963, and with 95% confidence, in vivo prostate translations were detected before exceeding 2.3, 2.5, and 2.8 mm in the AP, SI, and ML directions.

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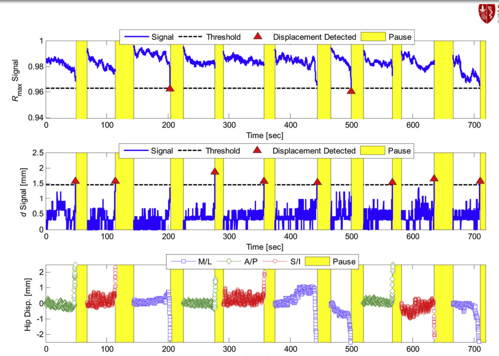
Online Image-based Monitoring of Soft-tissue Displacements for Radiation Therapy of the Prostate, IJROBP, 3(5), 08/2012

Demonstration of on-line monitoring

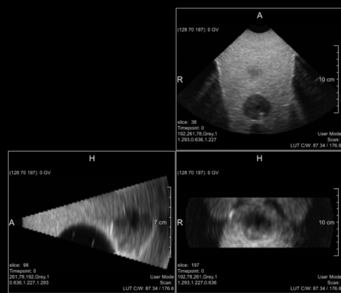


From 2D to 4D: pick your 3

field-of-view (FOV)

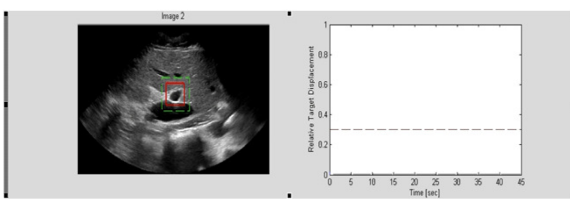
temporal sampling

spatial resolution



High-resolution real-time imaging with adequate FOV is possible!

Managing motion in dynamic targets



Beam On

Beam Off

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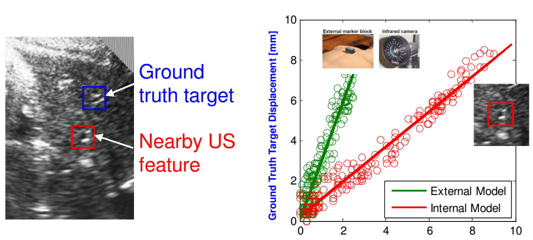
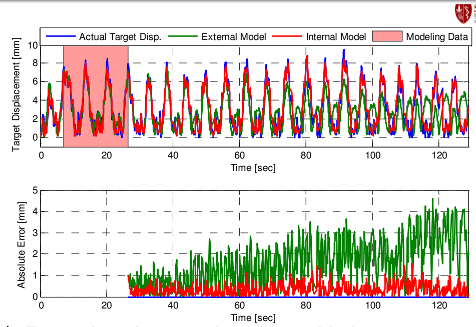
Experimental Method



Motion of ground truth target predicted using nearby US feature and external IR marker

Example



- External marker error increases with time.
- Internal US signal error remains low.

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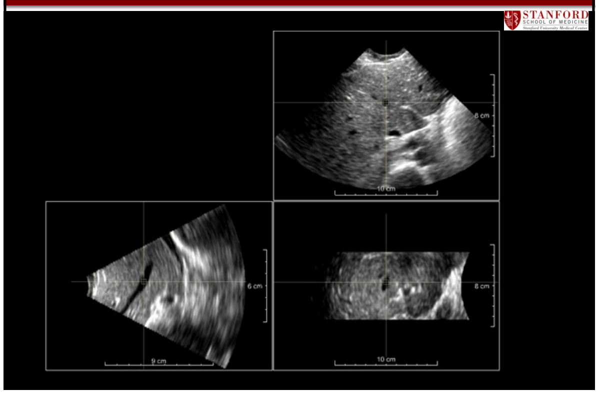
Liver Feature Monitoring



Conclusions

- *Online telerobotic ultrasound imaging over a timescale representative of therapy sessions is possible.*
- *Online motion detection before displacements exceed 3 mm is possible. Bi-plane imaging is expected to further improve performance and robustness.*
- *Continuous streaming of 4D data opens possibility for true 4D motion management.*

Conclusions

- *Simulation tools are expected to enable comprehensive studies on treatment planning strategies to account for the manipulator.*
- *Evaluation of long term effects of radiation on the transducer performance is required.*
- *Cross-validation against other modalities (radiographic imaging of fiducial markers) is ultimately necessary.*

Questions ?