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

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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


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

Robot interference with the LINAC?

Compact design to avoid gantry collisions.
Telerobotic Imaging for multiple sites

- Prostate Volunteer
- Liver Volunteer
- Kidney Volunteer

Image quality remotely maintained over 10 minutes

From 2D to Bi-plane to 4D

2D+time
Bi-plane+time (X-plane)
3D+time (4D)

1 GB/s Ethernet
Digital Navigation Link

From 2D to 4D: 2nd generation robot

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

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.
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

Selection of TDP threshold values

Selection of TDP threshold values

(b)

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<th>d=1.4 mm</th>
<th>R=0.963</th>
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~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

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.

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

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.

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?