Intrafraction prostate motion correction using a non-rectilinear image frame

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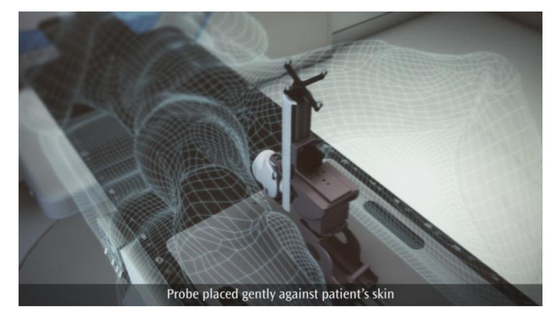
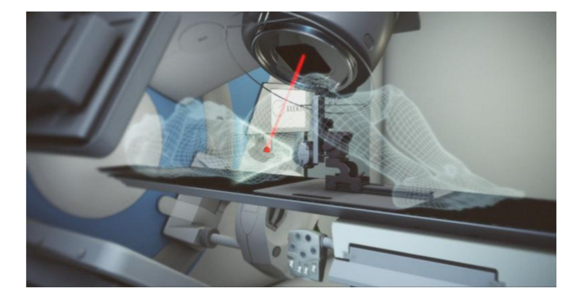
Motivation

- Prostate cancer is the most common cancer affecting men.
- External beam radiation therapy is frequently used for treatment.
- Despite careful positioning at the start of treatment, the prostate may move during the dose delivery.
- Thus, there is a need for intrafraction monitoring of prostate position.

TPUS prostate monitoring

- We are interested in monitoring prostate position during treatment using 3D ultrasound taken trans-perineally (TPUS)

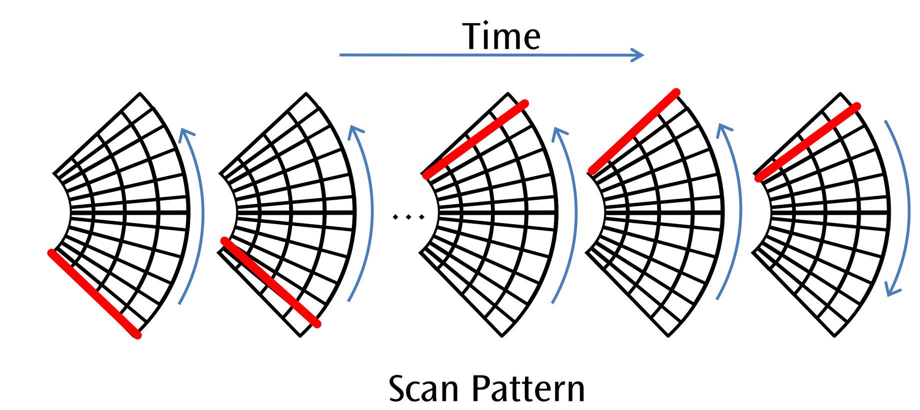




- TPUS imaging provides a non-invasive, non-ionizing means of prostate observation during radiation dose delivery.

Equipment

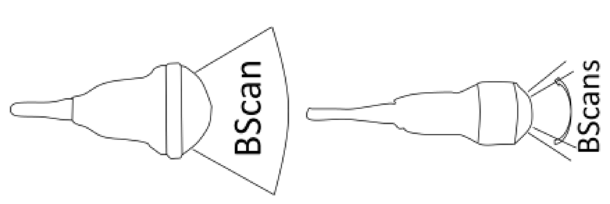
- 3D ultrasound sweeps were obtained using a m4DC7-3/40 Convex 4D probe (Ultrasonix, Vancouver, Canada) mechanically swept probe.



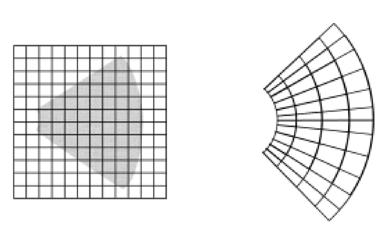
- Tracked images were captured and stored for offline processing using a modified version of the Elekta Clarity US-Guide system

Non Rectilinear Frame

Images captured by the mechanical probe fall naturally in a cylindrical coordinate frame.



Probe: Side View   Top View



Volume: Side View   Top View

$$\mathbf{X_w} = \mathbf{X_o} + \mathbf{D}\cdot\begin{bmatrix} i\cdot s_i \\ (j\cdot s_j + r)\cos(\alpha k) - r \\ (j\cdot s_j + r)\sin(\alpha k)\end{bmatrix}$$

Conversion from Pixel to World Coordinates

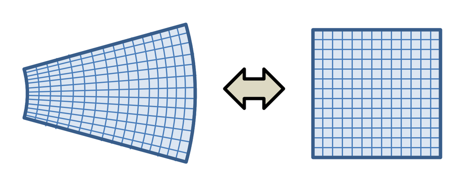
$$\mathbf{X_p} = \begin{bmatrix} u \\ \sqrt{v^2+w^2} - r/s_j \\ \dfrac{\tan^{-1}(v,w)}{\alpha}\end{bmatrix} \quad \begin{bmatrix} u \\ v \\ w\end{bmatrix} = \begin{bmatrix} 1/s_i & 0 & 0 \\ 0 & 1/s_j & 0 \\ 0 & 0 & 1/s_j\end{bmatrix}\cdot\mathbf{D}^{-1}\cdot(\mathbf{X_w} - \mathbf{X_o}) + \begin{bmatrix} 0 \\ r/s_j \\ 0\end{bmatrix}$$

Conversion from World to Pixel Coordinates

One limitation of the method is that for the cylindrical coordinate frame to remain valid, the probe must not move during acquisition.

Interpolation / Derivatives

Use of this coordinate frame in an intensity based registration framework requires the ability to interpolate image values at non-integer pixel positions, and to compute image derivatives relative to world space.



Interpolation is performed in the image space, which maps to a sector in physical space.

$$\frac{\partial \mathbf{I}}{\partial \mathbf{X_w}} = \frac{\partial \mathbf{I}}{\partial \mathbf{X_p}}\cdot\frac{\partial \mathbf{X_p}}{\partial \mathbf{X_w}}$$

$$\frac{\partial \mathbf{X_p}}{\partial \mathbf{X_w}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \dfrac{v}{\sqrt{v^2+w^2}} & \dfrac{w}{\sqrt{v^2+w^2}} \\ 0 & \dfrac{-w}{\alpha(v^2+w^2)} & \dfrac{v}{\alpha(v^2+w^2)}\end{bmatrix}\cdot\begin{bmatrix} 1/s_i & 0 & 0 \\ 0 & 1/s_j & 0 \\ 0 & 0 & 1/s_j\end{bmatrix}\cdot\mathbf{D}^{-1}$$

Image derivative $\left(\frac{\partial \mathbf{I}}{\partial \mathbf{X_w}}\right)$ with respect to world coordinates

X_p = [i j k]: pixel coordinates
X_w: world coordinates
X_o: origin
D: matrix of direction cosines

α: angular step
r: radial offset
s_i, s_j: pixel scales in i and j directions
u,v,w: intermediate values

Evaluation and Discussion

Image sequences were captured from healthy volunteers. The prostate position was tracked using sequential registration. The direct use of a non-rectilinear image was compared to results obtained with a typical reconstruct and register approach.

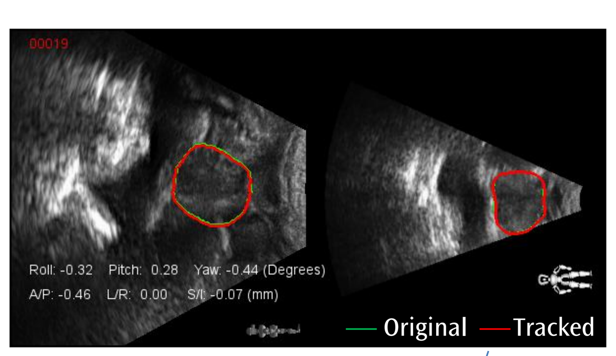
		Reconstructed		Cylindrical		Centroid
Case	# Vols	Time	σ	Time	σ	mTRE
P1S1	115	0.277	0.143	0.827	0.401	0.160
P1S2	115	0.197	0.102	0.533	0.273	0.636
P2S2	115	0.222	0.075	0.638	0.284	0.193
P2S3	115	0.208	0.069	0.562	0.206	0.265
P2S4	131	0.193	0.053	0.551	0.146	0.113
P3S1	115	0.306	0.203	0.864	0.424	0.619
Overall	**706**	**0.233**	**0.118**	**0.660**	**0.303**	**0.326**

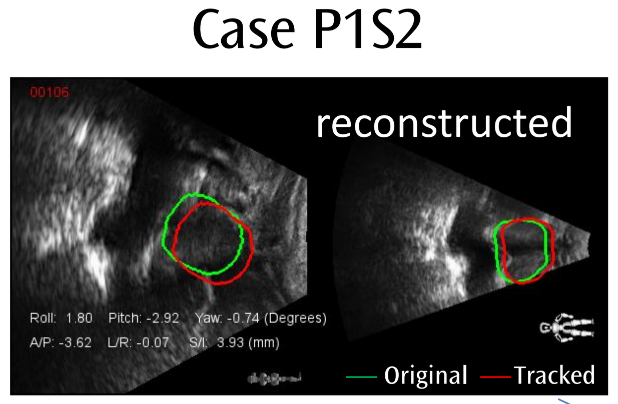
Mean registration time and positional difference between methods. Reconstruction requires an additional 2 seconds per image

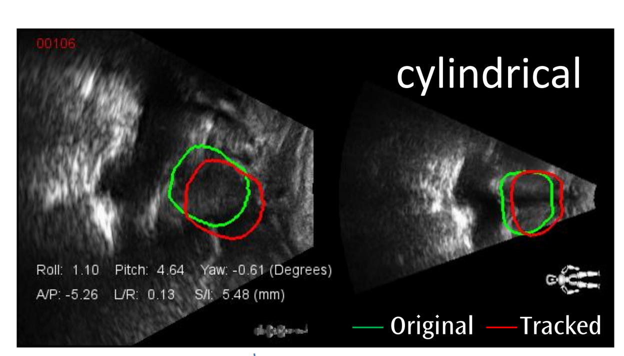
These results show that registration using cylindrical coordinates compares favorably with the use of a rectilinear image. While registration with the cylindrical image is slightly slower, there is a considerable overall time saving by avoiding reconstruction.

Selected Results on Typical Series

Case P1S2

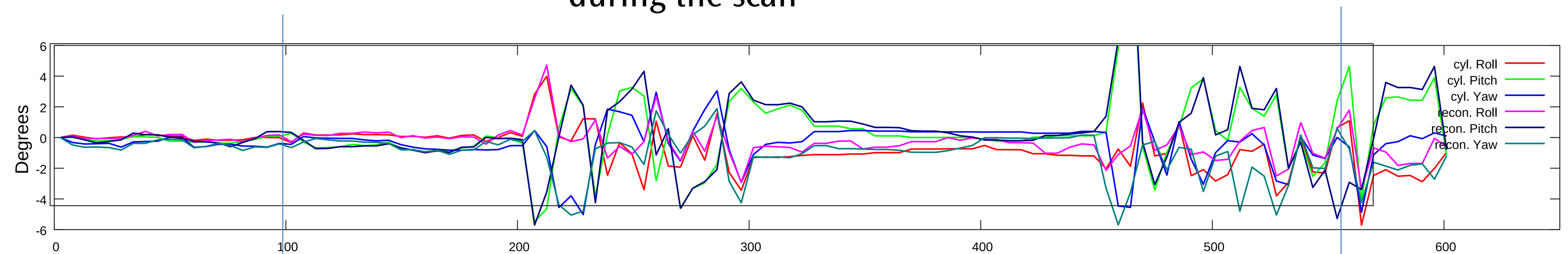


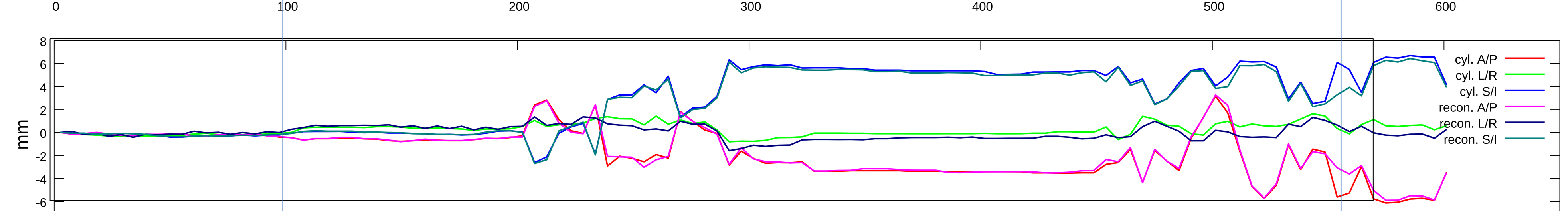




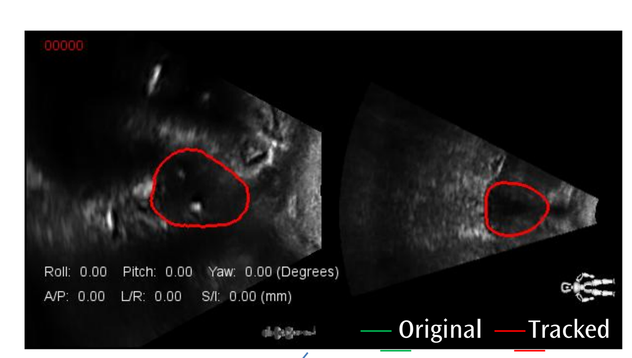
A typical case. Little movement has occurred at this point.

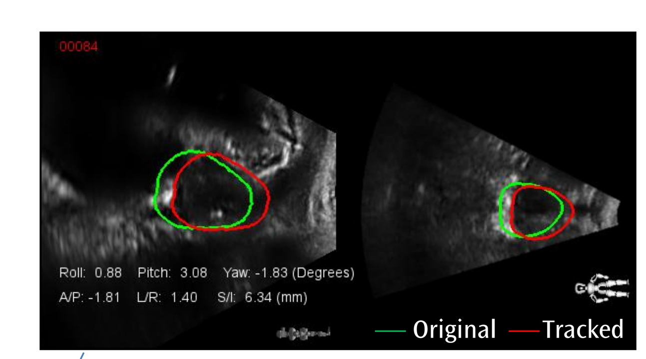
Here there is a difference between the two results, caused by distortion due to movement during the scan





Case P2S2

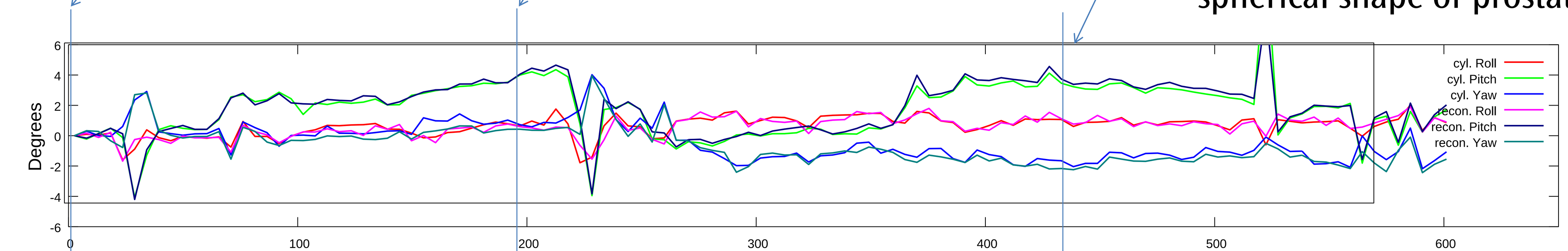


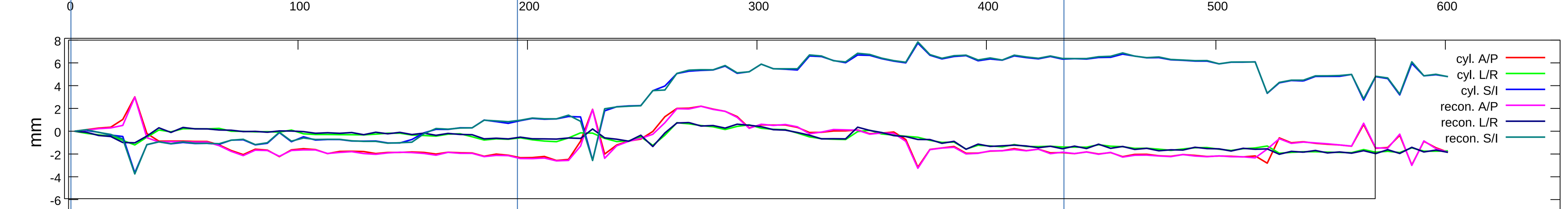


Initial Position

Relatively large rotation, Small posterior shift

Relatively large rotation and shift. Rotations are subtle to detect due to roughly spherical shape of prostate.





Brooks, R. Intrafraction Prostate Motion Correction using a non-rectilinear image frame. Presented at Prostate Cancer Imaging: Computer Aided Diagnosis, Prognosis and Intervention: International Workshop, held in conjunction with MICCAI 2011, Toronto, Canada. Sept. 22, 2011.