4D ultrasound calibration for radiotherapy guidance using automatic intramodality image registration

Innovation/Impact: Traditional ultrasound (US) spatial calibration methods require custom-built phantoms, assume explicit knowledge of phantom geometry, and/or rely on laborious segmentation of US image features. Our new method capitalizes on automatic 3D intramodality image registration to quickly and accurately calibrate 4D US systems using any available US phantom, regardless of shape or geometry. This advancement simplifies and accelerates the calibration process, allowing transformation of the image information to the frame of the linear accelerator (LINAC) for markerless soft-tissue target tracking using our robotic system.

Calibration Details: A chain of homogeneous transformations \( T \) are used to reconstruct the US data in the LINAC frame (Figure 1). The objective of the spatial calibration is to solve for the unknown transformation from the image to the US probe: \( p^{pr,T^{im}} \). To this end, we collect \( n \) US images \( (im) \) of a stationary phantom at different probe \( (pr) \) positions as the probe is tracked by a camera \( (cm) \). A specific point \( p \) in the first US image \( (1) \) can be transformed to the stationary camera frame via another arbitrary US image \( (i, j) \) as follows:

\[
\begin{align*}
T_{cm,pr}^{im,(i)} p^{im,(i)} &= T_{cm,pr}^{im,(j)} p^{im,(j)} & (1) \\
T_{cm,pr}^{im,(i)} p^{im,(i)} &= T_{cm,pr}^{im,(j)} p^{im,(j)} & (2)
\end{align*}
\]

The matrices \( T_{cm,pr}^{im,(i)}, T_{cm,pr}^{im,(j)} \) are provided by the optical tracker, and the matrices \( T_{im,(i)}, T_{im,(j)} \) are found by automatic 3D image-to-image registration using normalized mutual information (NMI) between images \( (i, j) \) and image \( (1) \) (Figure 2 a-b). Equating and rearranging (1) and (2),

\[
\begin{align*}
T_{cm,pr}^{im,(i)} = T_{cm,pr}^{im,(j)} & (3)
\end{align*}
\]

Using all \( n \) images collected during calibration, we arrive at a system of the form \( A^{i,j} X = XB^{i,j} \), where \( X = p^{pr,T^{im}} \). In robotics this problem is called "hand eye calibration", and several solution methods exist. We use an eigenvalue-based method\(^4\) to solve the system for \( p^{pr,T^{im}} \).

Evaluation of Calibration Accuracy: