Comparison of Methods for Tool Localization in Biological Tissue from 3D Ultrasound Data

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MOTIVATION

• Many surgical procedures consist of introducing a miniature surgical instrument such as a needle, or an electrode into biological tissue. The effectiveness of such procedures is enhanced, if the position of instrument in tissue is estimated in the course of intervention.
• 3D ultrasound (US) imaging modality allows inexpensive, flexible and fast acquisition of volume images that can serve for automatic object localization in biological tissue.
• Fig. 1 depicts a biological tissue comprising a thin metallic electrode. It is scanned by a 3D US scanner to provide us with volume images. To track the electrode in near real-time, an algorithm that automatically localizes the instrument in acquired data is needed.

METHODS

• We formalize a parallel projection of volume image \( I : \mathbb{R}^3 \rightarrow \mathbb{R} \) with a Parallel Integral Projection (PIP) transform \( P : \mathbb{R}^4 \rightarrow \mathbb{R} \) given by

\[
P_{\alpha}(u,v,\alpha,\beta) = \int_{-\infty}^{\infty} I(R(\alpha,\beta) \cdot (u,v,t)) dt
\]

where \( R(\alpha,\beta) \) is the rotation matrix in 3D space.
• The electrode axis can be determined from the maximum of the PIP transformation \( P_{\xi} \). Let \( (\nu_{\alpha}, \nu_{\beta}, \nu_{\gamma}) \) be the position of maximum, then the analytic form of the electrode axis is given by

\[
\mathbf{e}(t) = (0, 0, \nu_{\gamma}) + \nu_{\alpha} \mathbf{u} + \nu_{\beta} \mathbf{v}
\]

where \( \mathbf{u} \) and \( \mathbf{v} \) are the unit vectors parallel and orthogonal to the electrode axis.

• To accelerate the localization, the maximum of \( P_{\xi} \) is sought using the hierarchical mesh-grid method.

METHOD II – MODEL FITTING WITH RANSAC[2]

• Cubic polynomial \( I_{\Theta}(t) \) with twelve-element parameter vector \( \Theta \) models electrode axis.
• Distribution of voxel intensity inside electrode region is described by a priori estimated model \( b(d) \), that models voxel intensity at distance \( d \) from axis.
• Parameter vector \( \Theta \) is estimated by RANSAC using a cost function \( C(\Theta) \) given by

\[
C(\Theta) = \sum_{x \in A} \left( I(x) - b(d(x,t)) \right)^2
\]

where \( A \) is a set of voxels and \( d \) is the distance of voxel to axis.
• Parameter vector \( \Theta \) that minimizes \( C(\Theta) \)

\[
\Theta = \arg \min_{\Theta} C(\Theta)
\]

determines polynomial curve \( I_{\Theta}(t) \) that approximates the axis.

RESULTS

• \( \xi_{\alpha\xi} \) was used to quantify the method accuracy. It was defined as the maximum distance of the electrode determined by known endpoints \( E_1, E_2 \) from estimated axis.

NUMERICAL DATA

• FIELD II was used to simulate tissue of 50x50x30 mm containing a highly scattering cylindrical object of 20 mm in length and 150 \( \mu \)m in diameter. The simulations were set to provide a 3D sector data with 40° scan plane, 40° tilt angle and 65 mm depth of penetration, Fig. 2.
• We investigated the influence of algorithm parameters and data quality (background noise, electrode position and orientation) on localization accuracy, Tab. 1.

REAL ULTRASOUND DATA

• Tungsten electrode of 150 \( \mu \)m in diameter was inserted into polyvinyl alcohol cryogel phantom with acoustic properties of biological tissue. 3D ultrasound scanner Kretz Voluson 530D operating at 7.5 MHz scanned the phantom submerged into water, Fig. 3.
• With manually estimated \( E_1, E_2 \), the average \( \xi_{\alpha\xi} \) is 0.15 mm for the method I and 0.35 mm for the method II.

CONCLUSION

• We compared two developed methods for automatic localization of metallic electrode in biological tissue.
• The testing was performed both on simulated data with known electrode position and real 3D ultrasound data.
• The accuracy of both methods is on the order of hundreds of \( \mu \)m.
• Although RANSAC method is less accurate, it is more general and less computationally demanding.

REFERENCES