Localization of Surgical Instruments in Biological Tissue from 3D Ultrasound Images

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Many surgical procedures consist of introducing a miniature surgical instrument such a needle, or an electrode into biological tissue. For instance in biopsy, tissue samples are taken from a particular region of body by means of a thin needle. Conversely in breast cancer therapy, radioactive substance is injected near the tumor. In the field of neurobiological research, there are experiments where the electrical activity of a single neuron is recorded by a thin electrode needle. The effectiveness of such procedures is enhanced, if the position of instrument in tissue is estimated in the course of intervention.

At the outset, stereotactic frames were used for instrument localization. Horsley and Clarke, in 1908, described the first stereotaxy procedure on small animals. They used a frame fixed with respect to external anatomical landmarks to place an electrode at a specific point in the animal's brain. However, the position of intracranial point can not be derived from external landmarks with sufficient accuracy. In the last few decades, several medical imaging modalities were developed allowing to view anatomical information of human body as well as a surgical instrument in the course of intervention. Ultrasound imaging modality commonly used in medical diagnostics is particularly suitable for the localization task: short acquisition time permits real-time imaging; no ionizing radiation is involved; the resolution of modern systems is approximately one millimeter; purchase and operational cost is low compared to other medical imaging modalities.

We are working on a novel tracking system whose core consists of a 3D ultrasound scanner equipped with radio-frequency (RF) output. This system is tested on the problem of localizing a thin metallic electrode inside human tissue. The region of tissue where the electrode is located is scanned by the ultrasound machine and a 3D image is obtained. The goal of our project is to develop an algorithm that permits to automatically determine the electrode position with respect to the image coordinate system. Processing of ultrasound images is difficult for several reasons: due to speckle noise some portion of background voxels are brighter than electrode voxels; in case of total reflection of ultrasound beam there is a signal loss that results in irregular and incomplete electrode; as the spatial resolution differs in axial, lateral and azimuthal direction, electrode shape vary with position and orientation.

The localization problem was decomposed in two subtasks: (i) localization of electrode axis, (ii) electrode tip localization. We proposed two methods that permit to automatically determine the electrode axis. The first method is based on the observation that the parallel projection of the image is maximized when the image is projected along the direction parallel to the electrode axis [1]. This operation was formalized as a Parallel Integral Projection (PIP) transform. We show that the axis of the electrode can be estimated from the maximum of the PIP transformation. To accelerate the search for maximum, a hierarchical mesh-grid algorithm was implemented. In order to make the axis localization more general and faster, second algorithm based on model fitting was developed [2]. The input image is pre-segmented with a constant threshold whose value is derived from estimated Gamma distribution of voxel intensities. The electrode is described by a model that is composed of a polynomial parametric curve approximating axis and a distribution of voxel intensities given voxel-to-axis distance. The parameters of this model are estimated using the robust estimator RANSAC. To further improve the axis localization accuracy, optimization using the Nelder-Mead simplex method was implemented. Once the electrode axis is known, we proceed to tip localization. Voxel intensities are traced along estimated axis and the tip is the point where the intensity falls under predefined threshold. The threshold is set based on a priori estimated distributions of electrode, resp. background voxel given voxel intensity.

A series of tests on numerical phantoms simulated in the FIELD II program were performed to give quantitative value of localization accuracy. We investigated the influence of tissue speckle noise on the localization accuracy. Further, localization accuracy was evaluated when electrode position and orientation was varied. These tests show that the average axis localization accuracy is 0.15 mm, resp. 0.35 mm for the first, resp. second method. The average accuracy of tip localization is 0.95 mm. In order to test the algorithms on real ultrasound data, the 3D ultrasound scanner KRETZ was used to scan a cryogel phantom containing tungsten electrode of 0.15 mm in diameter. The results indicate that the algorithms are robust in terms of noise and irregularities of electrode and that the localization accuracy on real data is comparable to the accuracy achieved on simulated data.

References:

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[2] BARVA, M.; KYBIC, J.; MARI, J.M.; CACHARD, C.; HLAVAC, J.: *Automatic localization of curvilinear object in 3D ultrasound images,* Proceedings of SPIE International Symposium on Medical Imaging, 2005, pp. 455-462.

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