Seminar Paper Summary

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Section I. Introduction

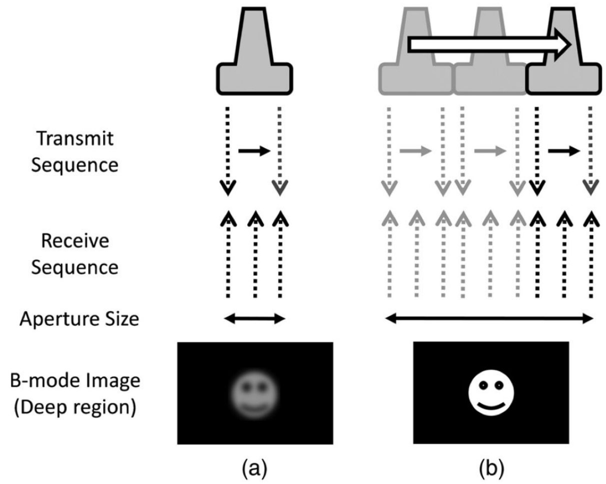
The procedure used to collect cerebrospinal fluid, known as "lumbar puncture" or "spinal tap", requires the careful injection of a epidural needle to the space between vertebrae of a patient lying on their side. The aim of our project is to develop a low-cost, portable medical device to deliver high-resolution ultrasound images in real-time in order to help guide physicians to deep targets. In addition to improving patient well-being and comfort, our project has the potential to save hospital administration hundreds of millions of dollars per year by reducing the complications stemming from blind lumbar punctures. In part due to the advances laid out in the subsequent papers, our project concept will have the advantages of high-quality visualization of the lumbar region during the time of insertion in addition to real-time tracking of the location of the needle tip.

Specifically, this summary review will examine the contents of two papers. The first is "*Synthetic tracked aperture ultrasound imaging: design, simulation, and experimental evaluation*" (Zhang et. al., 2016) and the second is "*Fusing acoustic and optical sensing for needle tracking with ultrasound*" (Cheng et. al., 2018). The first paper is an in-depth look at a reconstruction step in ultrasound imaging to synthesize coherent sub-aperture information at each position of a transducer and to form a final image with higher resolution and contrast. The second paper provides a short summary of a promising experiment that demonstrated the possibility of utilizing the photoacoustic effect to pinpoint a needle tip embedded with a piezoelectric sensor. Section II will cover the first paper and Section III will cover the second.

Section II. "*Synthetic tracked aperture ultrasound imaging: design, simulation, and experimental evaluation*"

<u>Summary of Goal, Key Results, and Significance</u>

The first paper explains the concept of Synthetic Aperture Imaging and how an ultrasound transducer can be tracked in its movement in order to use the relative motion between two frames to reconstruct information that would have been lost in between the two positions. In conventional ultrasound, a fixed number of elements generates and A-line, and by sequentially acquiring multiple A-lines, a B-mode image is formed. The resolution of the image is determined by the number and spacing of the elements. Using synthetic aperture, instead all the elements receive signals from a single source, each producing their own low resolution reconstruction, but then the accumulation of these images has the effect of focusing transmission waves, and a higher resolution image can be obtained.



This paper sought to understand the effects of changing parameters of synthetic aperture tracking on image quality, and implemented several tracking systems to recover coordinates of motion and to transform the coordinates of the probe positions. The figure below shows the coordinate systems involved in this paper's imaging experiment. The transformation from the tracking base frame to its tracked marker frame is defined as *B*, the transformation from the tracked marker frame to the ultrasound image frame is defined as X, and the transformation from the ultrasound image frame to the imaging target frame is defined as A. When the target is a single point, p is used to describe the point location in the ultrasound image. The motion applied to the ultrasound probe, the relative transformation between two poses from the ultrasound image frame, can be expressed as $M = X^{-1}B_i^{-1}B_jX$, where B_i and B_j correspond to two posed of the tracked marker. To introduce the motion M, the new probe pose is determined rom its original pose. When the original rigid body transformation is Bi, a new pose Bj can be expressed as $B_j=B_jXMX^{-1}$. In the reconstruction process, data collected at each pose are projected back into the original ultrasound image frame and summed up.

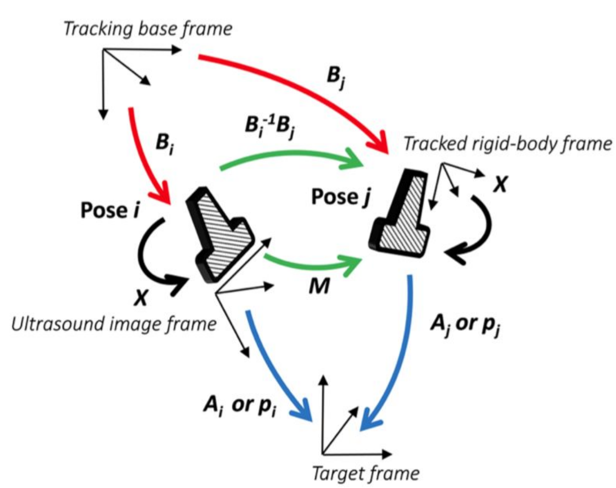


Fig. 2 The coordinate systems involved in synthetic tracked aperture ultrasound (STRATUS) imaging.

Results

To support this concept for synthetic aperture, the paper described an extensive set of experiments both in simulation and in a physical experiment. Images and the number of poses were tracked as the transducer was moved above a line phantom. In this paper, they chose to focus purely on translational motion, which itself provides the most basic scanning strategy. It can also be integrated onto a robotic arm or a rail as will be done in our prototype. This has the benefit of eliminating rotational error and simplifies our approach in utilizing this method, especially since the paper itself stops short of examining the effects of rotation as well.

One of the drawbacks to this paper, which was twelve pages of very dense reading, was that the results of these experiments were presented in their figures rather than a single tabulated form. As a result, no one figure can be inserted into this summary paper to provide an accurate description of the mathematical interpretation of the images. For the purposes of our project and this paper, it is more effective that the take-away be that SA will assist us in generating higher quality images and that we have a guide for implementing it ourselves.

Section III. "*Fusing acoustic and optical sensing for needle tracking with ultrasound*"

Summary of Goal, Key Results, and Significance

In this study, a needle tracking system was developed to provide accurate visual aid without requiring line-of-sight or chains of spatial transformations to recover coordinates inside of a patient, which opens the possibility for error propagation. The key result of this paper was that in an ideal environment, on average, submillimeter errors were achieved. This opens the possibility for future testing in *ex vivo* scenarios and other more realistic scenarios.

Necessary Background

The basis for this experiment hinges on the fact that two sources of partial position information can be fused to create a complete three-dimensional tracking system. Ultrasound imaging can be used to provide needle-tip detection and visualization and a mono-camera set-up can be used to segment the needle shaft. By fusing the information of the tip and of the shaft, it is possible to recover the relative location and orientation of the needle.

Technical Approach

The ultrasound sensor can provide point source information of the tip modeled as distance from the transducer. Active point sources can be observed in the US image even if it is outside of the imaging plane. Point sources are straight-forward to isolate from an image because they can be viewed as a bright intensity against a dark background. A circular arc can be parameterized to estimate out of plane locations and to transform the coordinate system. In this equation e_i refers to the lateral position of the segmented piezoelectric signal and d_i refers to its axial position. t is then the parametrized angle defining the rotation of this point about the ultrasound transducer's lateral axis.

$$\forall t = -90^o : 90^o : C(t) = \begin{bmatrix} e_i \\ d_i \sin(t) \\ d_i \cos(t) \end{bmatrix}$$

Below is a visual representation of the out of plane estimation taken from the paper.

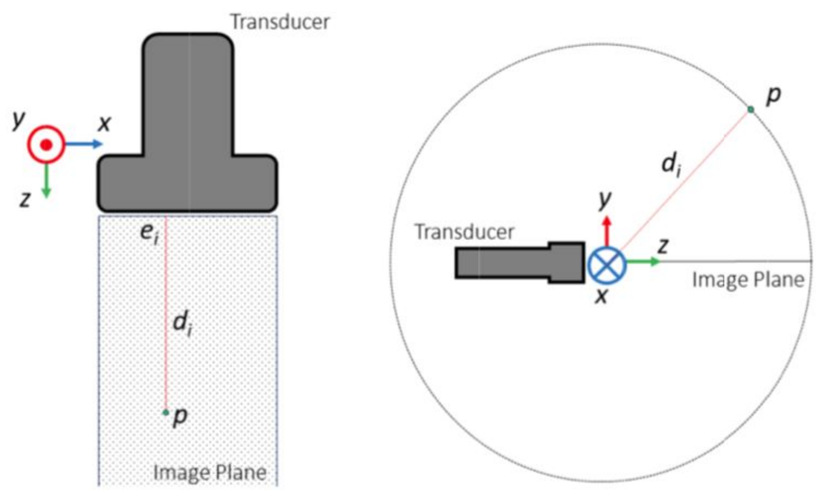


Figure 1. Out-of-plane estimation. Given the lateral coordinate and the distance between the point and the transducer element closest to it, the point must exist on a circle within the axial-elevational plane. [7]

The monocamera identifies the line that corresponds the needle shaft, but since it is from a single camera, the line cannot be identified with any depth certainty. Thus, the line is extended back out of the image of the camera in a hypothetical plane upon which the shaft rests at some unknown depth. By picking two points on the centerline, p_1 and p_2, the plane is defined by its normal, N, and vector, v, relative to the camera's optical center,

$$N = (p_1 - o)x(p_2 - o)$$
$$v = p_1 - o$$

This plane is used fused with the information from the ultrasound to find the intersection of the circular arc with the plane, which gives us the three dimensional location of the needle-tip once the coordinates are resolved.

$$(X * C(t) - o) \cdot N = 0$$

Experimental Design

This sensor fusion was tested by attaching a PZT element to a rigid tube to emulate an element placed at the end of a tip and using two types of experiment. The first placed the PZT element at the tip directly inside the US imaging plane and the second compared the computed positions to a set of known locations inside of a Cartesian stage. The experiments were performed inside of a water tank.

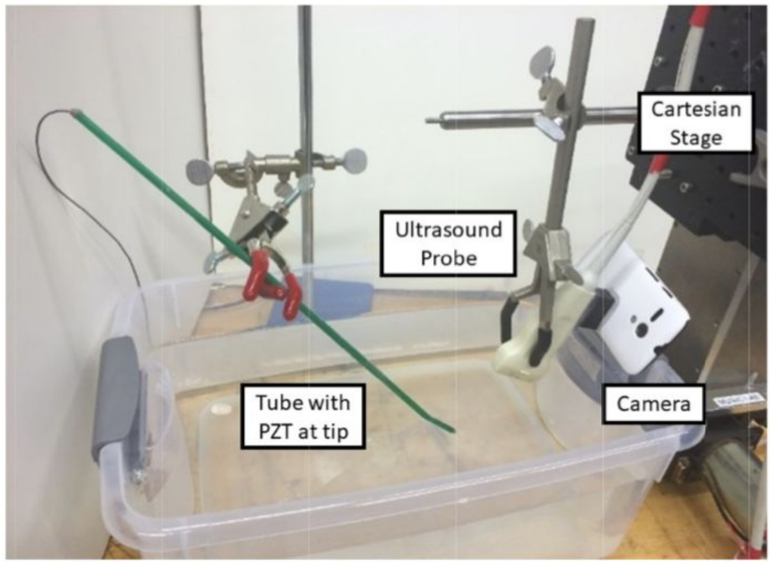


Figure 3. Experimental setup with a cartesian stage, a camera, and ultrasound probe, and the piezoelectric element.

Assessment

The first experiment yielded results that resulted in errors of 0.63 mm and 0.18 on two independent poses. Using their relative accuracy measurement for the second experiment, they derived a minimum, maximum, mean, and standard deviation of 0.02mm, 2.15mm, 0.61mm, amd 0.61mm respectively. This paper itself remarks that these results are very promising, however, they depend entirely on the controlled environment in which the experiment took place. The first example of this would be that a fabricated tool was used instead of a real needle, which requires special manufacturing. A needle will require its own specific camera segmentation methods and does not account for needle bending, which introduces errors to the estimation. The work to realize this system in a practical sense is yet to be finished, and it must be tested in new scenarios to determine whether the assumptions still hold.

I found this paper to be thorough in its approach to identifying the solution and the protocol for needle-tip tracking, but it lacked details in its explanation of the mathematics and of the results of the experiments. Despite it being a short, concise paper, it at times relied too strongly on the readers sense of spatial abstraction. Additionally, the figures provided in the paper would be better understood through a more thorough description of the point-by-point procedure and a tabulated results portion, rather than providing simply the subsequent image, which may be misinterpreted to someone not reading carefully. Nor does it actually specify that this image belongs to the second experiment. It must be intuited by the reader.

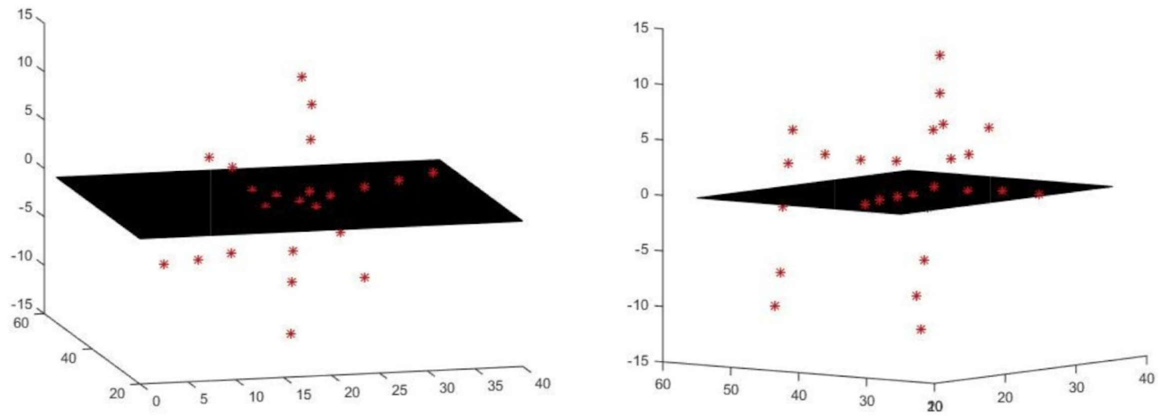


Figure 4. Subsets of detected PZT positions with respect to the ultrasound image plane (black plane).

In conclusion, this paper assists in the development of our project because it offers us a solution for tracking the needle tip. We intend to tackle the shortcomings described previously in our own testing or instead conclude that another alternative solution, such as another photoacoustic method, would better serve our purposes and our desired form factor.

References:

- Haichong K. Zhang, Alexis Cheng, Nick Bottenus, Xiaoyu Guo, Gregg E. Trahey, and Emad M. Boctor "Synthetic tracked aperture ultrasound imaging: design, simulation, and experimental evaluation," Journal of Medical Imaging 3(2), 027001 (8 April 2016).
- Cheng, Alexis, et al. "Fusing acoustic and optical sensing for needle tracking with ultrasound." Medical Imaging 2018: Image-Guided Procedures, Robotic Interventions, and Modeling. Vol. 10576. International Society for Optics and Photonics, 2018.