Gabor-based Detection of Needle Planes in 3D Ultrasound Data Volumes

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1. Introduction

Medical interventions with needles have a wide variety of applications in diagnosis and treatments, e.g. in regional anesthesia and biopsy. During these interventions, medical imaging modalities, particularly ultrasound (US), are used to locate and guide the needle in order to minimize risks to the patient and improve health outcomes. However, performing the procedure is very challenging, as any hand motion may exclude parts of the needle from the image and lead to an erroneous needle placement. Alternative external tracking systems are not widespread, since they require additional equipment in the operating room, need specific skills to operate the additional systems and they add costs to the US system and the needle. In contrast, a 3D US system that is extended with an appropriate image-based analysis can overcome the previous limitations in US-guided interventions and improve the guidance of the needle without requiring any external tracking systems [1]. Nevertheless, performance of such algorithms is limited to the properties and quality of US, such as low signal-to-noise ratio, speckle noise, imaging artifacts and anisotropy in images.

In our study [2], we present an algorithm to reliably detect and track a needle in 3D US using a directionally-sensitive spectral transformation, i.e. 3D Gabor transform. In this paper, we present the detection results in several *in-vitro* and *ex-vivo* situations and show the robustness of our method in cases of different complexity.

2. Methodology

Figure 1 depicts the main stages of our system, involving: (A) detecting the needle in the first acquired volume, (B) tracking it over time, and (C) visualizing the needle in the volume. We now briefly address each stage.

Needle detection subsystem is divided into five algorithmic steps [2]. First, the 3D US volume is enhanced and normalized using 2D processing techniques. Second, 3D Gabor transformations of the volume are calculated for different filter orientations, designed to be sensitive to needle-like structures. Third, for each voxel, a feature vector is composed from the analyzed Gabor responses, being invariant to the needle orientation and small changes in brightness and appearance. Then, discriminative classification is applied to detect the candidate needle voxels. Finally, needle axis position and orientation in 3D are approximated from the detected voxels using a robust line fitting method.

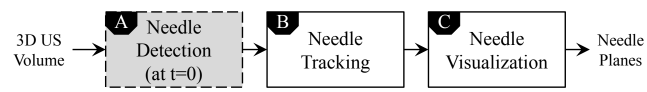


Figure 1: Proposed system block diagram

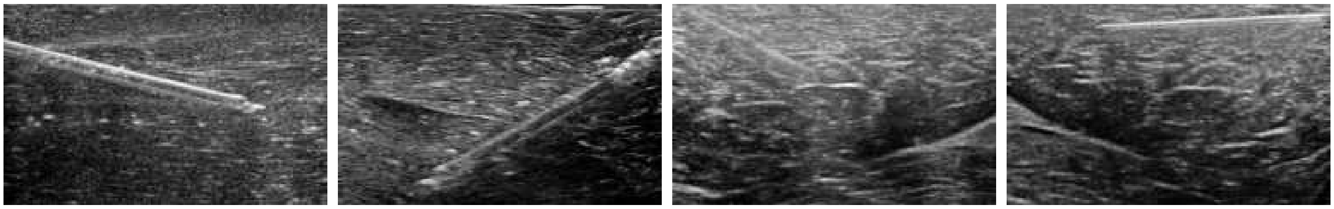
Needle tracking over subsequent acquisitions is achieved from needle approximate position at the previous time moment. We propose a tracking algorithm, which locally searches for the brightest axis with a Gradient Descent strategy. At each iteration, one of the needle endpoints is displaced by one voxel towards the minimum detection error until it converges. Moreover, tracking can be performed to increase the needle detection accuracy, which is limited due to the Gaussian envelope in Gabor transformation.

Needle visualization is proposed to optimally comply with the US-guided needle intervention practices. Therefore, a cross-section containing the full-length needle is visualized to the operator.

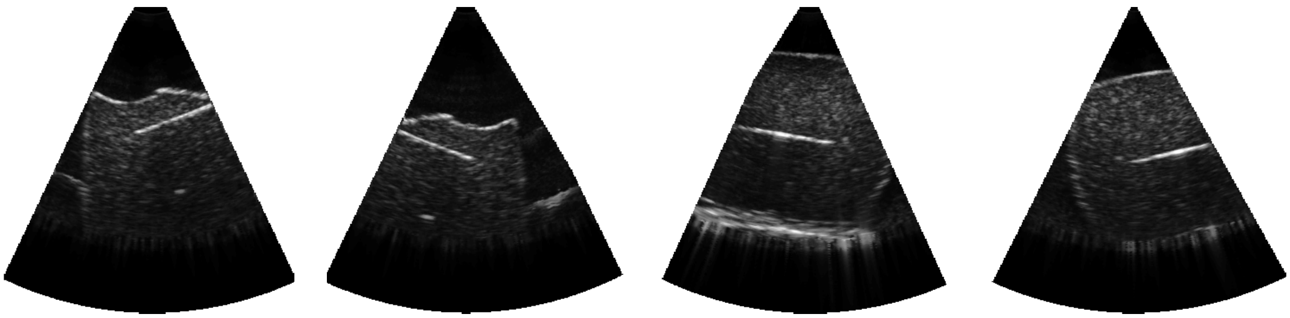
3. Experimental Results

The proposed needle detection algorithm is applied to 16 different 3D US volumes of chicken-breast [2] and PVA cryogel [3] phantoms, which are acquired using a 5-13 MHz motorized linear array and a 5-8 MHz curved array transducer, respectively. Needles with different thicknesses are inserted at various angles in the phantom, while volumes are acquired. The ground-truth voxels belonging to the needle are annotated manually for each volume.

The average performance of our proposed algorithm is evaluated on the two datasets and is shown in Table 1. The needle position error, ε_p, is calculated as the average of the point-line distances between points on the ground-truth axis and the detected needle axis. The orientation error, $\varepsilon_{\mathbf{v}}$, is the angle between detected and ground-truth orientations.



(a) Examples of needle detection in datasets of chicken breast phantom acquired with the 3D motorized linear array transducer.



(b) Examples of needle detection in PVA cryogel phantom acquired with the 3D curved array transducer.

Figure 2: Examples of detected needle planes.

Table 1: Performance of our needle detection algorithm.

Dataset	Needle Diameter	ε_p	$\varepsilon_{\mathbf{v}}$
Chicken breast	1.47 mm (17G)	0.65 mm	2.2°
	0.72 mm (22G)	0.90 mm	3.5°
PVA cryogel	∼ 0.60 mm	0.81 mm	6.5°

As shown in Table 1, for different datasets, the proposed Gabor-based method can successfully detect the needle in 3D. Furthermore, we observed during experiments that individual position errors for each trial are less than 2 mm showing 100% success rate in both datasets of linear and curved array transducers.

The performance of the needle tracking is evaluated on the chicken-breast phantom data, while we assume the needle position in the previous frame. The needle is tracked accurately with an error of less than 1 mm for small movements but fails for larger movements of greater than 4 mm. However, such larger movements between subsequent acquisitions are not realistic during an intervention.

Figure 2 portrays examples of the detected planes from the 3D US volumes, which contain the full-length needle and its tip. Figure 2a shows results in chicken-breast phantom and Figure 2b visualizes results in PVA cryogel. Compared to the PVA cryogel, structures in the chicken breast can represent human anatomy more realistically. However, because this dataset is acquired by a linear array transducer, increasing the needle insertion angle dramatically reduces the needle visibility, which can degrade the automated detection performance.

4. Conclusions

We have proposed a novel needle detection algorithm for 3D US volumes, which is solely based on a directionally-sensitive Gabor transformation without employing any external tracking devices, modifications of the acquisition system or the needle itself. Our tracking technique is based on Gradient Descent error minimization that efficiently finds the needle in subsequent acquisitions and can improve the detection stability. We visualize the needle and its tip with 2D cross-sections of the 3D US volume.

Experiments on different acquisition setups show high accuracy of the proposed algorithm in detecting and tracking the correct plane in several *in-vitro* and *ex-vivo* situations. With slight modifications of Gabor wavelets, discriminant features between the needle and other structures are modeled and different types of needles can be accurately detected in various datasets. Future work will focus on detecting shorter and steeper needles to increase the reliability of the system. Real-time implementation will enable the proposed technique to be used for live intervention support.

References

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