Real-Time 3D Needle Shape Tracking Using Fiber Bragg Grating Sensors for Prostate Percutaneous Interventions

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Purpose

During prostate needle insertion, the gland and therefore targets move resulting in targeting inaccuracy. To compensate for this error, in a previous study we proposed robotic bevel-tip needle steering under live MRI. One important drawback is that tracking a flexible (20G) needle under real-time MRI is inaccurate due to the needle artifact and the image update frequency is relatively slow (>200 ms). As an alternative solution, we embedded some FBG strain sensors along the needle shaft at certain locations and reconstruct the needle shape from this information. Compared to the previous study on this topic by others, the following development have been done: 1) this study is extended to needle of higher gauge (thinner), 2) we guarantee below 0.5 mm accuracy at the needle tip for *all insertion depth*, 3) we extended it to bevel-tip needles (through modelling and mathematical formulation), 4) we visualized the 3D shape of the needle in 3D Slicer which is a commonly used planning and navigation software for prostate interventions, 5) our needle tracking is real-time.

Methods

Figure 1 shows an overview of the methodology. In order to estimate the needle 3D shape, the needle curves in *x-y* and *x-z* planes (*x* is the needle axis) should be estimated individually. For this reason, we measure the strain at three certain locations along the needle (x_1, x_2, and x_3) for each plane. Strain has linear relationship with the second derivative of the curve and consequently it is possible to estimate the *x-y* and *x-z* curves. This means two fibers, each with 3 FBGs with different wavelength are required. An identical extra fiber (again with 3 FBGs) is added for temperature compensation (i.e. finally in 120 degree configuration in cross section view - Fig. 1). The fibers were embedded into the inner stylet. The optimum locations of the FBGs were found from mechanical modeling of the beveled needle followed by computer simulations. After building the needle, we connected the fibers to an FBG interrogator to attain wavelength shift for each FBG. Through a novel calibration procedure, the wavelength shift of each FBG was related to the corresponding strain value. We post processed the strain data in MATLAB and generated 3D curve equation for the needle. Eventually, the needle curve equation was sent from MATLAB to 3D Slicer for visualization. The communication of MATLAB and 3D Slicer was established using OpenIGTLink.

For calibration and evaluation, a setup as showed in Fig. 2 was prepared. The needle was held by a pin vise attached to a 2-DOF (linear/rotary) micro-stage (Fig. 2). The stage can translate vertically with 10 µm resolution thus enabling needle-tip deflection with high accuracy. The rotary stage with 1º resolution provided rotation of the needle for enabling deflection in different planes. In order to detect the first moment of starting deflection, a scale with 0.001grams resolution was used. A sharp blade was placed on top of the scale to enable point contact between the scale and the needle. The needle tip was deflected from 0 up to10% of the needle cantilever length. This experiment was repeated for three depths, (27mm, 75mm, 110 mm) and for two angles (θ=0° and 90°, where θ is the needle orientation).

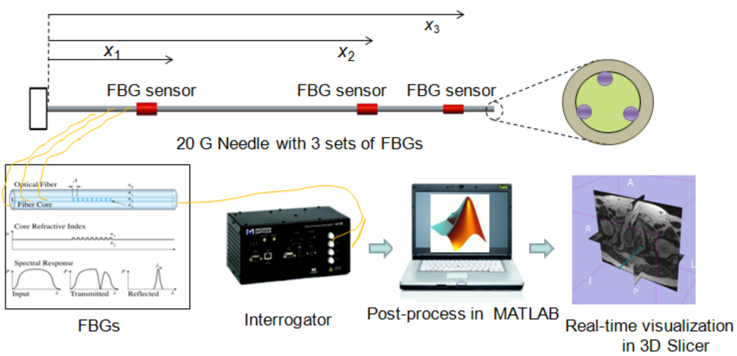

Figure. 1. Real-time needle 3D shape tracking using FBGs and visualization in 3D Slicer

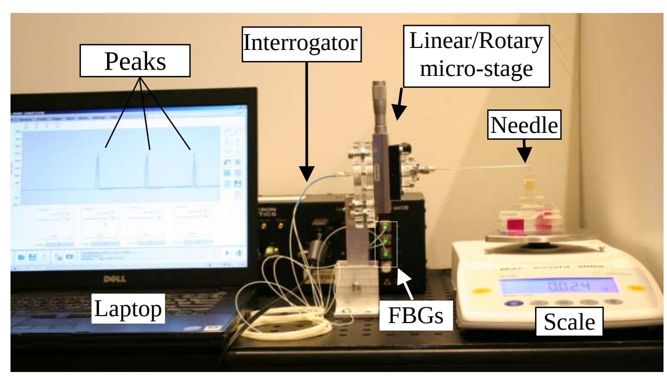

Figure 2. Calibration and experimental setup.

Results

The optimal locations of the sensors were found to be x_1= 30 mm, x_2=79 mm, x_3=99 mm after mechanical modeling of the beveled needle and computer simulations. Three calibration matrices (each 3x2) were found for each location. Based on them, the needle shape and tip location in 3D were estimated. The estimated results then were compared to the actual translation of the micro-stage. The errors were below 0.5 mm for all cases with the exception of depth= 110 mm at 0 degree (max- 0.8 mm).

Conclusions

In this study we developed a needle tracking system using FBG sensors for flexible bevel-tip needles. The needle was specifically designed for a real scenario, i.e. robot-assisted bevel-tip needle steering under MRI guidance for prostate interventions. Results showed needle tip tracking error below 0.5 mm in all insertion depths, covering all clinically relevant insertion depths in transperineal prostate needle placement procedures. These results prove the feasibility of this needle tracking approach.