Instrumented needle sensors positioning method based on experimental data

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Pierre-Loup SCHAEFER, Grégory CHAGNON and Alexandre MOREAU-GAUDRY
Univ. Grenoble Alpes, CNRS, Grenoble INP Institute of Engineering Univ. Grenoble Alpes, TIMC-IMAG, F38000 Grenoble France
Contact: pierre-loup.schaefer@univ-grenoble-alpes.fr

Instrumented needle are interesting tools to use during minimally invasive surgery procedures. Their use allows to reconstruct the shape of the needle during the procedure by using the data of the embedded sensors of the needle. Thus the shape of the needle is accessible to the physician in real time and without further use of medical imaging. This papers focuses on the reconstruction process of the shape of the needle and specially on the positioning of the sensors by proposing a novel method based on experimental data.

1 Needle Shape Reconstruction

1.1 Sensor data processing

An instrumented needle is composed by a standard medical needle and a certain number of sensors. This article focuses on needles with strain sensors embedded on its surface. The technologies of the sensors themself are beyond the scope of this article [1, 4]. We just consider that the data retrieved from the sensors give the strain on the surface of the needle. The sensors are placed following the geometry presented in the Fig. 1.

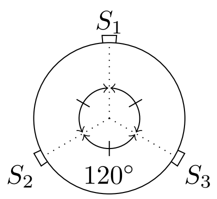

Figure 1: *Three strain sensors S_1, S_2, S_3 placed on a circular section of a needle with a 120° angle between them.*

Thus the sensors are placed by groups of three on sections of the needle and with 120 degrees between them. Each of this group is called a triplet. These positions allows for each triplet of sensors to retrieve two scalar values representatives of the bending of the needle at the triplet locations: the curvature κ and the bending angle θ. Eventually the values of all triplets of sensors constitute a discretization of the curvature function and the bending angle functions.

1.2 Geometric reconstruction

The values of curvature $(\kappa_i)_{i=1,n}$ and bending angle $(\theta_i)_{i=1,n}$ retrieved from the sensor triplets are interpolated to give the curvature estimate κ_{est} and the bending angle estimate θ_{est}. These estimates are then used to reconstruct the shape of the needle itself. According to the hypothesis that the mechanical torsion of the needle is negligible the material frame of the needle is a rotation minimizing frame (RMF) [2,6], which is a special type of moving frame. Let (T, N_1, N_2) be the RMF of the needle, we then have the following differential system:

$$\frac{d}{ds}\begin{bmatrix} \mathbf{T}(s) \\ \mathbf{N_1}(s) \\ \mathbf{N_2}(s) \end{bmatrix} = \kappa(s)\begin{bmatrix} 0 & cos\theta(s) & -sin\theta(s) \\ -cos\theta(s) & 0 & 0 \\ sin\theta(s) & 0 & 0 \end{bmatrix}\begin{bmatrix} \mathbf{T}(s) \\ \mathbf{N_1}(s) \\ \mathbf{N_2}(s) \end{bmatrix}$$

Solution of this system represents the evolution of the RMF of the needle all along its length. By integration it is then possible to obtain the full shape of the needle.

2 Strain Sensors Locations

The reconstruction of the shape of the needle raises the question of the sensor locations: What locations give the most accurate needle shape reconstruction? These locations are defined as *optimal locations*. The optimal locations are defined as the locations that minimize the error of reconstruction of the needle shape. Thus the problem of sensor locations can be considered as a minimization problem. To evaluate the relevancy of sensor locations, existing needle shapes are used. For any locations the sensor data are simulated with these reference needle shapes and are then used to obtain the reconstructed needle shape. The comparison of those two shapes then gives the reconstruction error. On the difference of the methods available in the literature [1,4], the method of sensor location optimization presented in this article is based on experimental data and is fully three-dimensional.

2.1 Study of a experimental needle set

The sensor locations method is based on experimental data coming from a needle insertion study. The study was carried out on a set of CT scans of needles insertion into pig shoulder. The choice of pig tissue is due to its similar properties with human tissues.

The study consists in retrieving the property of the needle shape from the CT scans. The different steps include:

- Segmentation
- B-spline smoothing
- Rotation minimizing frame computation

Finally for each needle is associated an estimate of its curvature and an estimate of its bending angle.

2.2 Minimization problem

The research of the sensor optimal locations is a problem of dimension n, where n is the number of sensor triplet. It falls under the category of Mixed Integer Nonlinear Programming category of minimization problem. Thus special algorithms have been deployed to obtain the solutions [3, 5].

3 Results

Table 1 expose the results of the optimal locations computation from the experimental set of pig data for a 200 mm needle.

Number of sensor triplets	Sensor triplets optimal locations (mm)
1	81
2	28, 101
3	25, 77, 136
4	9, 40, 95, 144
5	11, 34, 77, 128, 171

Table 1: *Optimal sensor triplet locations obtained from the pig needle set. Locations are expressed as distances in millimeters from the proximal extremity of the needle.*

Fig. 2 presents the reconstruction error with the optimal sensors locations obtained compared to arbitrary equidistant sensor locations. We observe from Fig.2 that the use of the optimal locations over equidistant locations decreases both the mean and the maximum of the reconstruction error. Notably the mean of reconstruction error decrease by 17 % to 57%.

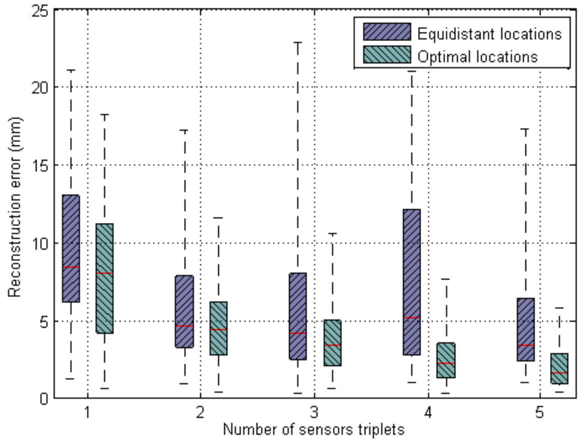

Figure 2: *Boxplot of the reconstruction error of the pig needle set for a number of sensors triplets between 1 and 5 according to sensors locations. Ends of the whiskers represent minimal and maximal reconstruction errors.*

4 Conclusion

This paper presented a novel method to compute the optimal sensor locations of an instrumented needle based on experimental data and fully three-dimensional. The results presented here expose the gain of accuracy obtained with the use of the optimal locations computed on the same set of experimental data. Further process of validation conducted on clinical data (not presented here) also confirm the gain of accuracy made by using the optimal locations. We conclude that the methode developed and presented here offers a gain of accuracy of the needle shape and reliable sensor locations for insertions of an instrumented needle in different type of tissues.

The work presented in this paper is supported by the French ANR-12-TECS-0019.

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