Trajectory Estimation of Flexible Needle Using PVA Tissue Material

Shijian Zhao¹, Dedong Gao¹*, Mengxiao Zhao¹ and Jiajie Fu¹

¹School of Mechanical Engineering, Qinghai University, Xining 810016, China

*Corresponding author: gaodd@qhu.edu.cn.

Abstract. In order to determine the movement trajectory and characteristics of puncture needle in tissue, a series of puncture is selected for the puncture of PVA prosthesis. The image captured by CCD camera is preprocessed, and the starting coordinate point and target in the image are extracted. A fitting model based on least squares method is proposed to fit the radius of puncture needle. Comparing the simulation trajectory of forward kinematics and experimental trajectory, the experimental results show that the fitting model has a high success rate over 93% in the trajectory radius of the prosthesis puncture needle, and has a high success rate, stability and accuracy. It has a certain reference significance for the future path planning and guidance process.

1. Introduction

Recently, needle insertion has been widely used in clinic, but the traditional rigid needle cannot plan its trajectory well to get around the obstacles such as blood vessel and nerve[1]. Also for its low accuracy, it may cause secondary injury to patients during insertion. The flexible needle is made by nickel titanium, which let it have good elasticity, for the tip of the needle has an asymmetric diagonal angle, when insert into the tissue, subjected to asymmetric force the flexible needle deflects along the direction of force. There for, he bevel-tip flexible needle has good maneuverability and can bypass obstacles to reach the target[2]. As a minimally invasive surgical technique, needle insertion is widely used in clinical practice such as biopsy, epidural injection of spinal, near-range radiotherapy, anesthesia and ablation[3,4]. Needle insertion different situations have different precision requirements, usually, such as proximity radiotherapy, anesthesia and biopsy require mm-grade needle puncture accuracy, when the operation involves infants, eyes and ears, etc., the accuracy of the needle puncture is required to reach the um-grade[5].

How to control the insertion needle to carry on the specified route puncture has become the current difficulty, use the robot assisted needle insertion control technology has become a hot research topic in recent years for it has ability to accurately control the injection volume and needle tip direction[6,7]. The main point in robot assisted needle insertion controls technology is path planning and barrier avoidance technology. Recently, although a large number of relevant literature on the needle path planning problem has been studied, but because the flexible puncture needle is an incomplete system and the existence of tissue deformation leads to target migration and complex organizational structure and many other factors[8]. Most flexible needle model is divided into kinetic model and kinematics model. The kinetic model establishes the relationship between the force of needle tip and the deflection of needle tip. There are two ways to solve this problem. First, install the force sensors in the needle body. The force data is using building the friction model[9,10], and second, modeling and
analyzing the force of the needle tip directly[7,11]. Most of the dynamic models are based on static analysis, which cannot deal with the multiple rotation of flexible needles effectively, and the model is more complex and stays in the theoretical analysis stage. In 2005 Webster and other experiments show that in ideal conditions the sharp of flexible needle is insertion along the ARC path of the fixed radius, and the azimuth of the arc curve can be changed by changing the angle of the bevel-tip[8,12].

Then a large number of relevant literature is based on Webster et al.[8,13-16] to study kinematics, path planning and obstacle avoidance techniques of inclined tip flexible puncture needle. In 2005, Okazawa et al. designed a handheld maneuver[17], combined with software to puncture through the needle tip direction of the control needle, and in 2006 proposed a segmentation algorithm based on Ough transform, and the deflection of the needle body linear fitting[18], However, linear fitting of the needle body is not suitable for practical application. In 2007, Davneet et al.[19] analyzed the bending characteristics of the flexible needle, and proposed the use of rotating needle to control the trajectory of the needle body in the tissue, the purpose of controlling the trajectory of the needle body is achieved by adjusting the duty-free ratio of the needle body during rotation. In addition, HuoBenyan et al.[20] aiming at the relationship between control quantity and path, an algorithm based on multi-objective particle swarm is proposed, the model is simplified, and the efficiency is improved. However, the characteristics of biological tissue will change over time, resulting in path failure, and because the difficulty to accurately locate the pinpoint position within the biological tissue, how to solve the feedback problem has become a problem to be solved. In 2007 Gao et al.[21] established the kinematics model of puncture needle by using parameter method. By simulating and validating the model of the recording shows that, it has relatively accurate accuracy. However, it has not been verified experimentally. In this paper, a model is designed to extract the coordinates of the starting point, the target point and the radius of the needle. In the experiment, the image is collected by using CCD camera. After preprocessing the image, the parameters are extracted and the needle trajectory is simulated. The experimental results show that the model has a high accuracy, which has a certain reference significance for the future needle trajectory planning.

2. Forward kinematics model
When bevel-tip flexible needle insert the tissue, many factors determine the puncture trajectory of the needle. In the model of geometric approximation, we make the following assumptions about the insertion system: First, there is no delay between the needle tip and the needle seat. Secondly, when the needle inserts the tissue, the tissue does not cause deformation of the needle body that affects its trajectory. The last, the position of the trajectory is entirely determined by the needle tip shape, and the radius value of the needle trajectory is a certain value in the tissue.

Forward kinematics is used to calculate the motion trajectory of the needle body. It mainly includes a few control variables: needle pitch angle ($\alpha$), needle rotation angle ($\beta$), injection volume ($L$) and the bending radius value of needle body ($r$). In the process of injection, the transformation of coordinates is divided into two main steps. First, before insert the needle adjust the value of $\beta$ to select the insertion angel. Secondly, translation coordinate system $O_mX_mY_mZ_m$ to coordinate system $O_nX_nY_nZ_n$. The coordinate transformation matrix is as follows:

$$\|T(\beta, L) = P_{bt}(Z, \beta)_{\text{Trans}} h, 0, d) \| = \begin{bmatrix} c\alpha & -s\alpha & 0 & 0 & 1 & 0 & 0 & h \\ s\alpha & c\alpha & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & d \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c\alpha & -s\alpha & 0 & 0 & 0 & 0 & 0 & h \\ s\alpha & c\alpha & 0 & 0 & 0 & 0 & 0 & d \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$
Third, change the value of $\alpha$, rotate coordinate $OnXnYnZn$ around $Zn$ axis to get coordinate $OnXoYoZo$. Therefore, the coordinate transformation matrix is as follows:

$$
egin{bmatrix}
    c\beta & 0 & s\beta & 0 \\
    -s\alpha & c\alpha & 0 & cah \\
    0 & 0 & 1 & d \\
    0 & 0 & 0 & 1
\end{bmatrix}
$$

Where $\beta = \frac{L}{r}$, $h = r(1 - \cos\beta)$, $d = r\sin\beta$, $s\alpha = \sin\alpha$, $s\beta = \sin\beta$, $ca = \cos\alpha$, $c\beta = \cos\beta$.

By repeating the above two steps, the coordinate transformation in the whole puncture process is established. In addition, the coordinate transformation of needle insertion is shown in Figure 1.

When the needle tip is from the initial moment to the puncture to paragraph I, the position of the needle tip relative to the global coordinate system can be expressed as follows:

$$
^{gT}_{0T}r = ^{gT}_{0T}r(\beta, L) L^{-1} = ^{gT}_{0T}r(\beta, L) = ^{gT}_{0T}\prod_{k=1}^{I-1}r(\beta, L)
$$

Where $I = 1, 2, \ldots, n$. $^{gT}_{0T}$ is the homogeneous transformation matrix in needle-tip coordinate system relative to global coordinate system. Therefore, the position coordinates of the needle tip relative to the global coordinate system can be described in any period.
3. Experiments setup

To verify the accuracy of the model and the extracted data, a puncture needle was used to insert the PVA tissue. Where the puncture experimental platform shown in Figure 2.

In this experiment, polyvinyl alcohol (PVA) is used as a soft tissue phantom. The ratio of polyvinyl alcohol, dimethyl sulfoxide and distilled water was 8:60:40. After heating and stirring at 90 degrees for 6 hours, then standing at 20 degrees below zero for 10 hours and thawing for 3 hours, the PVA tissue was made.

The system has 3 degree of freedom (DOF) to that the needle can move, feed and rotate relative to the soft tissue during the insertion. A CCD camera is mounted above the PVA tissue to collect images. The CCD camera is used to take pictures of the whole needle body, which is as shown in Figure 3. The Figure 3 shows a series of insertion trajectories of the needle in soft tissue. The type of needle we are using is 18~23g hakko puncture needle. The bevel of needle is 20 degrees and the length is 200mm. The size of tissue is $100 \times 100 \times 20 \text{mm}^3$. Both type of needle is insert the PVA tissue in 2mm/s. In all experiments, the needle without deflection.

4. Data extraction

4.1. Extraction of needle trajectory

In the process of extracting the above basic parameters, the image taken by CCD should be pre-processed first. Firstly, the image is processed by binarization. Using binarization to image can make needle body more prominent in image and filter out needle-independent tissue structure. The value we choose here is 0.85, as shown in Figure 4 a). Thinning the needle in the image by using the skeleton processing of the image, as shown in Figure 4 b). The trajectory of the needle can be extracted by thinning the image. In addition, the trajectory of the needle which is shown in Figure 4 c). As can be obtained from Figure 4 c) the trajectory of a needle body consists of several coordinate points.
4.2. **Radius fitting**

By using the coordinate points, the radius of the needle in tissue could be determined. For the Hough circles transformation is inefficient and computational complexity is large. We here use the ordinary least squares to fitting the radius of puncture needle. The function formula of the ordinary least squares is as follows:

$$f = \sum \left( \sqrt{(x_i - x)^2 + (y_i - y)^2} - R \right)^2$$  

Where $x_i$ and $y_i$ is the coordinate points of the needle. $x$, $y$ is the center coordinate points of the needle body trajectory, $R$ is the radius of the needle.

For the ordinary, least squares the quality of sitting punctuation is very important. In order to ensure the accuracy of the fitting process, the generation of outliers in the original data should be reduced. Therefore, the generation of interference points should be reduced in image denoising, thresholding and filtering.

5. **Verification**

By using the trajectory coordinate points, the radius of the needle body is determined. The simulation trajectory of the needle body is obtained by bringing the needle coordinate points, target coordinate points and radius values into the forward kinematics model. The simulation and experimental trajectory shown in Figure 5.
In the needle insertion experiments, the type of needle included with inner core and without inner core. The simulation and experimental error result are shown in Table 1. Table 1 shows that the error between simulation and experiment is less than 7%, which the deviation ranges are all below 4%.

| Needle type | With inner core | Without inner core |
|-------------|-----------------|--------------------|
|             | Average Error (%) | Deviation Range    | Average Error (%) | Deviation Range |
| 18g         | 1.41103          | 1.28339            | 2.49968           | 1.28339         |
| 19g         | 2.31193          | 1.5396             | 5.09432           | 1.5396          |
| 20g         | 0.43969          | 1.44891            | 2.09591           | 1.44891         |
| 21g         | 3.33652          | 3.38101            | 3.53084           | 3.38101         |
| 22g         | 2.55718          | 0.273              | 1.60456           | 0.273           |
| 23g         | 2.47023          | 0.93764            | 1.95708           | 0.93764         |

6. Conclusions and future work

In this paper, a fitting model is established to combine the trajectory of the puncture needle with the experimental verification of the established forward kinematics. The CCD camera is using to take image in the experiments. In order to improve the accuracy of the fitting process, the image is pre-processed by binarization and noise reduction. After thinning the image, the radius of the needle in the image is fitted by the ordinary least squares. And the key coordinate points in the needle body puncture are extracted. By compared the experimental trajectory and the simulation trajectory of forward kinematics, the results shown that the model of fitting needle trajectory has high accuracy and stability which provides some reference significance for the future path planning.

In the future work, we will use the camera to record the result of deflecting one and more times during puncture needle puncture. By analyzing these results, we will be able to understand the puncture trajectory of puncture needle in more detail, and have some reference significance for the future puncture needle path planning. In addition, the radius measurement of the puncture needle should be extended to the animal tissue, and the trajectory and characteristics of the puncture needle in animal tissue should be studied by using B-ultrasonography to collect the image. This paper will take these issues as the content of future research.

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