Robotic Guidance of Flexible Needle for Percutaneous Therapy

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Abstract **- Flexible needle insertion for percutaneous therapies is formulated in this paper as a trajectory planning problem of a linear beam, supported by virtual springs. Using this simplified model, the forward and inverse kinematics of the needle is solved analytically, providing a way for simulation and path planning in real-time. Using the inverse kinematics, the required needle basis trajectory can be computed for any desired needle tip path. It is shown that the needle base trajectory is not unique and can be optimized to minimize the lateral pressure of the needle body on the tissue. Experimental results of robotically-assisted flexible needle trajectory tracking are provided.**

I. INTRODUCTION

One of the most common procedures employed in modern clinical practice involve percutaneous insertion of needles and catheters for biopsy and drug delivery. Percutaneous procedures involving needle insertions include vaccinations, blood/fluid sampling, regional anesthesia, tissue biopsy, catheter insertion, cryogenic ablation, electrolytic ablation, brachytherapy, neurosurgery, deep brain stimulation, minimally invasive surgeries and more.

Complications are due, in large part, to poor technique and needle placement [1]. Physicians and surgeons often rely only upon kinesthetic feedback from the tool, correlated with their own mental 3-D visualization of anatomic structures. It was shown in [2], that as the needle penetrates the tissue, the tissue deforms and even straight needle misses the target. Thick and nonflexible needles are easily pointed to the target in existence of visualization system, but their manipulation causes large pressure on the tissue. Moreover, straight needles are not suitable for making curved paths, if obstacle avoidance is required.

Needle insertion causes the surrounding soft tissues to displace and deform. DiMaio *et al.* [2] used finite elements simulation for determining such displacements[2]. Using this approach, Alteroviz *et al.* [4] suggests a way to predict seed placement error in prostate brachyterapy procedure and correcting for this error by choosing appropriate straight needle insertion point. Because of its intensive computation, the method does not allow online correction of the placement error.

Current methods and techniques are all use straight, rigid needles since they are easier to control and their trajectory is well defined. On the other hand, thinner needles are more flexible and thus causing less pressure and damage to the tissue. They allow making curved trajectories and easier obstacle avoidance. On the other hand, flexible needle navigation deep inside the tissue is very complicated - the system has non-minimum phase behavior and is not intuitive to control.

Flexible needle steering was first addressed by DiMaio *et al.* [3]. To solve the inverse kinematics of the needle, iterative numerical computing of the flexible needle's Jacobian is suggested. The computation involves solving for two-dimensional finite element mesh of the tissue and iterative nonlinear flexion of a beam and requires nine independent computations for devising the Jacobian elements. The computation complexity does not allow real-time simulation and control of the system.

The present investigation suggests a simplified model that allows fast path planning and real time tracking for needle insertion procedure. The future goal of this work is creating an image based closed loop system for automatic flexible needle insertion.

II. THE VIRTUAL SPRINGS MODEL

Modeling of flexible needle is based in this investigation on the assumption of quasistatic motion, so the needle is in equilibrium state at each step. It is known that biologic soft tissue deflection is nonlinear with strain, but for small displacements, locally, we can assume linear lateral force response, based on work of Simone *et al.* [5] and [6]. The forces exerted by the tissue on the needle are modeled as lateral virtual springs distributed along the needle curve plus friction forces tangent to the needle. Since the tissue elastic modulus differs as function of strain, we update the virtual spring's coefficients according to the elastic modulus corresponding to the current strain, and linearize the system at each step.

The concept is illustrated in Figure 1.

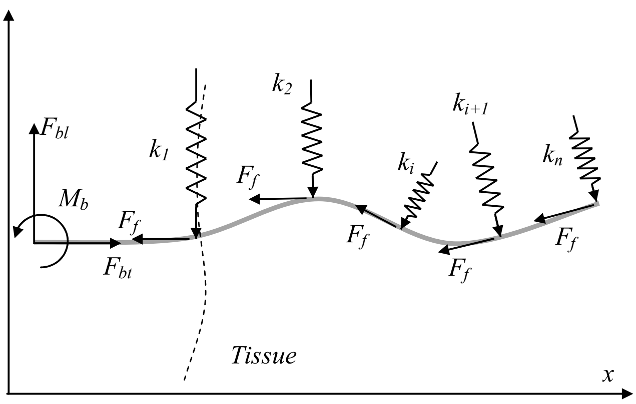

Fig. 1. Virtual springs model: the tissue's reaction is modeled by distributed virtual springs.

As the shape of the needle changes, the location and orientation of the virtual springs change as well. The stiffness coefficients of the virtual springs are determined either experimentally or using preoperative images by assuming empiric values for known tissues and organs.

A. The linearized system solution

Initially, assuming small displacements, the needle is approximated by a linear beam subjected to point forces as shown on Figure 2. With appropriate elements spacing, this approximation is close to a flexible beam on elastic foundation model.

At each joint, the force applied by the virtual spring is proportional to the spring's displacement from its initial position:

$$F_i = k_i\left(w_i - w_{0i}\right) \qquad \textbf{(1)}$$

where k_i is the virtual spring coefficient, w_i - displacement at point i, and w_{0i} - is the position of freed spring i.

Since the forces are a function of the deflection, this problem cannot be solved by superposition. It can be solved only globally for all the elements of the beam. We define each element as the part of the beam between two neighboring forces. Thus the first element is the part of the needle outside of the tissue, and the rest of the elements are distributed along the inner part according to the level of discretization. Each element behaves as a linear beam subjected to shearing forces at its borders. Since we assume linear flexible beam, the displacement of each element is given by a third degree polynomial. We adopt the nodal degrees of freedom from finite elements theory, in which the coordinates are specifically identified with a single nodal point and represent a displacement or rotation, having clear physical interpretation. The displacement *y(x)* has the form:

$$y(x) = N_1\phi_1 + N_2\phi_2 + N_3\phi_3 + N_4\phi_4 \qquad \textbf{(2)}$$

N_1 ,N_3 are the coordinates and N_2, N_4 are the slopes at $x=0$ and $x=l$ respectively. ϕ_i are the shape functions of third degree.

Substituting boundary conditions as displacement and slope at the base and tip of the needle, one ends up with $4\times n$ equations - 2 at each side and 4 for each internal node, which yields the global matrix equation:

$$\left[K\right]\overline{N} = \overline{Q} \qquad \textbf{(3)}$$

where K is the matrix of coefficients of $N_{i,j}$ - elements degrees of freedom. N is the vector of $N_{i,j}$, where i is the number of the element and j is number of degree of freedom, Q are the free coefficients.

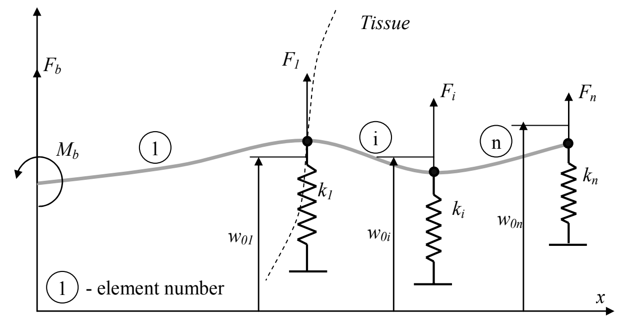

Fig. 2. Linear system model. Flexible beam subject to a number of virtual springs.

B. The 3 DOF forward kinematics

The above solution solves for the displacements and rotations of the needle for 2 DOF of needle base - vertical translation y and slope θ. But the main translation of the needle is in x - axial direction. Applying axial translation to the non-compressible needle means that the outside tissue part of the needle becomes shorter by the size of translation Δx. And an additional element of length Δx is added to the last element. Assuming that the last *(n+1)* element is relatively small, and the forces on it create negligible moments, its shape is taken as straight line, having the slope of the last element.

Summarizing, given 3 displacements of the 3 DOF of the needle's base, we are now able to calculate the 3 DOF translations of the needle tip, thus completing the forward kinematics solution.

C. The 3 DOF inverse kinematics

In an actual needle insertion problem, more importantly is the trajectory of the tip of the needle. First, there is a need to hit the target with the tip; second, the obstacle organs should be avoided. This is the problem of inverse kinematics namely, for a given position and orientation of the tip, calculate the translation and orientation of the needle base.

Equation (3) can be written as:

$$\left[\begin{array}{ccc|cc} 1 & 0 & \cdots & 0 & 0 \\ 0 & -1 & \cdots & 0 & 0 \\ \hline & \tilde{K}_{21} & & \tilde{K}_{22} & \\ & & & & \end{array}\right]\begin{pmatrix} N_{11} \\ N_{12} \\ \vdots \\ N_{n3} \\ N_{n4} \end{pmatrix} = \begin{pmatrix} Y \\ \theta \\ \vdots \\ \vdots \\ \vdots \end{pmatrix} \qquad \textbf{(4)}$$

In the forward kinematics scheme, one can solve for $N_{i,j}$ for a given base translation Y and rotation θ. Note that the last two elements of vector N are the translation and rotation of the tip. But in the inverse kinematics problem, the translation and rotation of the tip - N_{n3}, N_{n4} are known and the unknowns are the translation and rotation of the base - Y and θ or N_{11} and N_{12}. Since in the last two equations two variables are known, one can write Eq (4) as:

$$\left[\widetilde{K}_{21}\right]\widetilde{\widetilde{N}} = \widetilde{\widetilde{Q}} - \widetilde{K}_{22}\begin{pmatrix} N_{n3} \\ N_{n4} \end{pmatrix} \quad \textbf{(5)}$$

$$Y = N_{11}$$

$$\theta = N_{12}$$

where $\widetilde{\widetilde{N}}, \widetilde{\widetilde{Q}}$ are the original vectors $\overline{N}, \overline{Q}$ without the last two elements. $\widetilde{K}_{21}$ is (n-2)×(n-2) matrix and equation (5) can be solved for $\widetilde{\widetilde{N}}$ and therefore for Y and θ, which is the solution of the inverse kinematics.

D. Path planning

Simple linear path is straightforward. The main challenge is avoiding obstacles, while applying minimal pressure on the tissue, especially life important organs. In presence of obstacles, the best path should have minimal curvature of the needle. The path planning problem thus reduces to finding the shortest curve, connecting the target and needle insertion point, and avoiding obstacles. The insertion point on skin surface may make a difference. It can either be defined by the algorithm or constrained by the doctor.

In a planar case, the needle tip has 3 DOF and the path includes also the orientation of the needle tip. For the most common needle insertion procedures, like biopsy or drug delivery, the orientation of the needle tip along the path is of less importance. As will be shown below, tip orientation is essential for needle base motion and lateral pressure on the tissue.

E. Trajectory tracking and optimization

Trajectory tracking problem means computation of the needle base position and orientation for a given tip trajectory. To solve this problem, full simulation of the needle insertion is required, since every step is dependent on the previous history of insertion. As explained above, it is possible to reach the desired position with different tip orientations. Since in the needle insertion procedure, orientation of the tip is of less importance, one can reach the desired position with different possible tip orientations. One option is to maintain the needle as close as possible to straight line in order to diminish lateral forces, as is modeled below.

The sum of the needle deflections is given by S:

$$S = \min \sum_{i=1}^{n}\left(w_i^2 + \theta_i^2\right) = \min \sum_{i=1}^{n}\sum_{j=1}^{4} N_{ij}^2 \quad \textbf{(6)}$$

From Eq. (5), nodes displacements are functions of the desired tip orientation. Differentiating Eq. (6) with respect to θ_t and equating to zero yields:

$$\frac{dS}{d\theta_t} = \sum_{i=1}^{n}\sum_{j=1}^{4} 2N_{ij}\frac{dN_{ij}}{d\theta_t} = 0 \quad \textbf{(7)}$$

Eq. (7) is used to for the extra unknown -the slope of the last element N_{4n}.

III. NEEDLE INSERTION SIMULATION

The following example shows needle tip sine wave tracking that simulates avoiding an obstacle in the tissue. For simplicity, we draw the virtual springs as a compressible mesh below and above the needle, since the tissue is on both sides. As the needle penetrates deeper into the tissue, additional virtual springs are introduced. The insertion trajectory, where the tip is tangent to the trajectory is shown in Fig. 3 while the same tip trajectory but with minimal lateral tissue pressure is shown in Fig. 4.

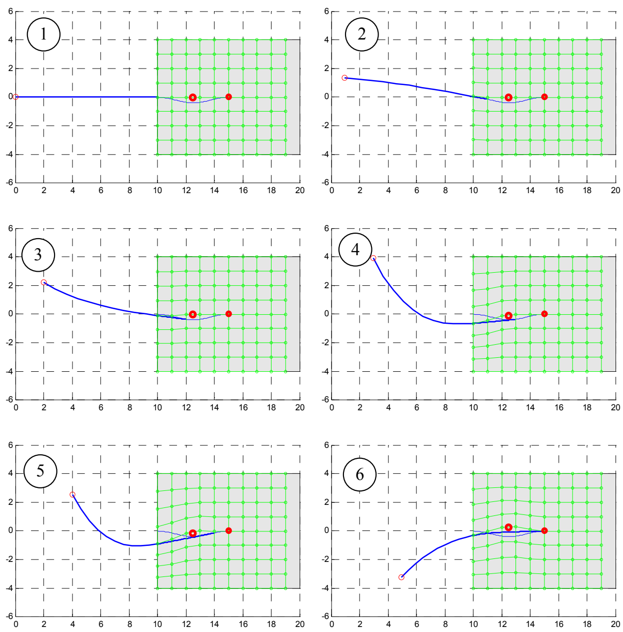

Fig. 3. Needle insertion trajectory with tip oriented tangent to the path.

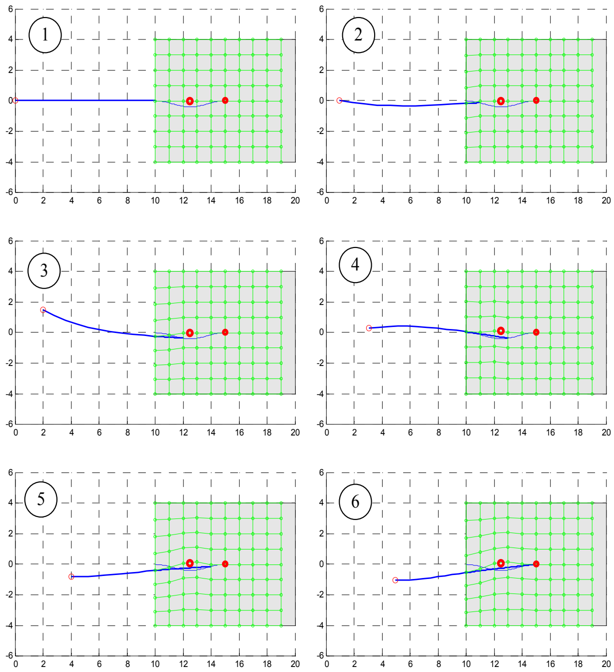

Fig. 4. Needle insertion trajectory while minimizing lateral pressure on the tissue.

IV. EXPERIMENT

A qualitative experiment was conducted to verify the feasibility of the suggested flexible needle guidance. The experimental system, Fig. 5 consists of a spinal needle 22G×90mm – outer diameter 0.711mm, inserted into chicken breast slice of 8mm thickness by a six Degrees-Of-Freedom (DOF) RSPR parallel robot [7] equipped with ATI Nano17 6 DOF force sensor. With proper lighting it was possible to see through the tissue and get reasonable quality images. The tissue is placed in a 100mm×100mm frame and constrained in one plane between two glass plates.

Two metal pieces were inserted into the tissue prior to the experiment – one for the target and one for the obstacle. The robot was required to follow the path, computed with the above algorithm, avoiding the obstacle and hitting the target. The images corresponding to simulation steps above are shown in Fig. 6.

As can be seen, the path followed by the needle tip is similar to the preplanned path avoiding the obstacle and hitting the target.

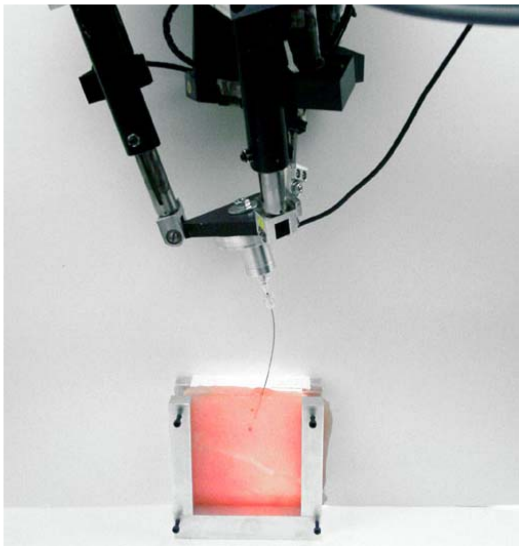

Fig. 5. Flexible needle insertion experiment system. RSPS 6 DOF parallel robot inserting 22G×90mm spinal needle.

V. CONCLUSION

This investigation develops the planar linearized model approximation for flexible needle insertion problem. Using this model, the inverse and forward kinematics of needle insertion can be obtained in one step, solving low dimensional linear system of equations. Path planning and it's optimization for minimal tissue lateral pressure were developed. It was found that this model can be solved in a closed form for a given needle tip trajectory. Relaxing the requirement of tip orientation to be tangent to path at each point greatly decreases the base stroke and the pressure exerted on the tissue.

We performed a qualitative experiment confirming the proposed concept. The needle trajectory was similar to the preplanned, avoiding an obstacle and hitting a target. Future research is focused on nonlinear beam approximation and close loop control utilizing an imaging system.

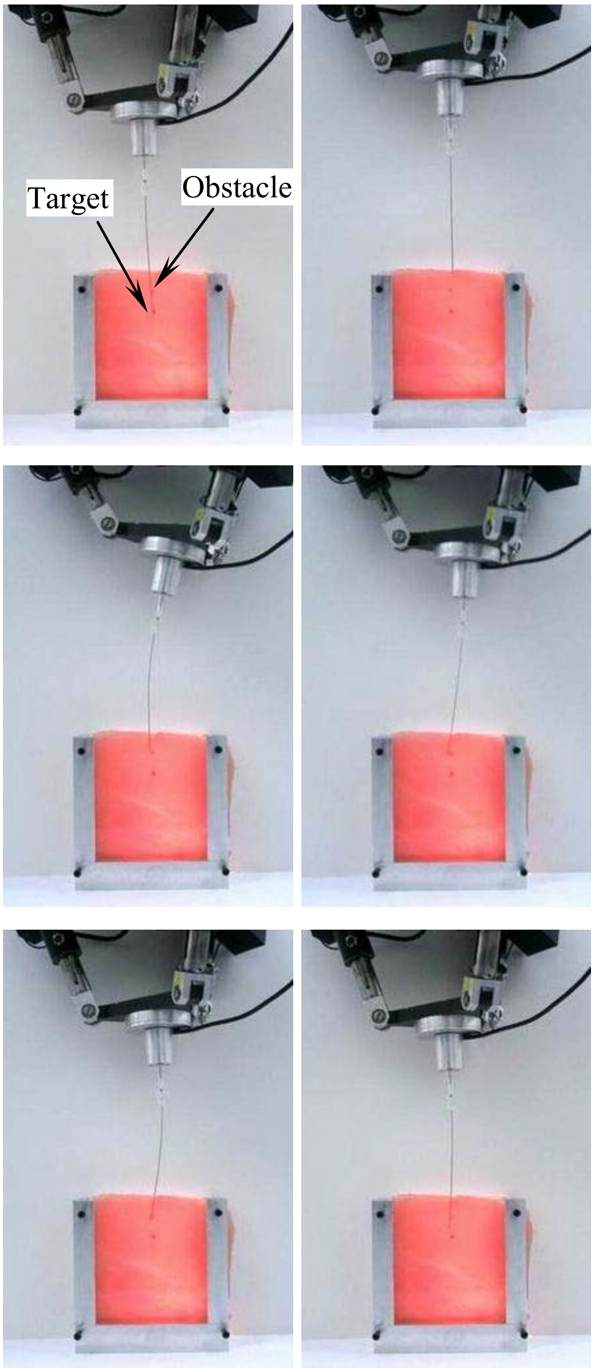

Fig. 6. Robot poses and needle trajectory during the flexible needle insertion.

IV. REFERENCES

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