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# Soft-Tissue Modeling and Image-Guided Control of Steerable Needles

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*Abstract*— **In this paper, we exploit a fuzzy controller on a flexible bevel-tip needle to manipulate the needle's base in order to steer its tip in a preset obstacle-free and target-tracking path. Although the needle tends to follow a curvature path, spinning the needle with an extremely high rotational velocity makes it symmetric with respect to the tissue to follow a straight path. The fuzzy controller determines an appropriate spinning to generate the planned trajectory and, the closed-loop system tries to match the needle body with that trajectory. The swine's brain tissue model, extracted from an in-vitro experimental setup, is a non-homogenous, uncertain and fast-updatable network to model real tissues, needle and their interactions providing the essential visual feedback for the control system. The simulation results illustrate a precise path tracking of the bevel-tip needle based on the fuzzy controller's commands with two degrees of freedom.**

## I. INTRODUCTION

NEEDLE surgery is one of the most complicated fields of minimally invasive surgeries which has attracted a number of researchers [1]-[3]. When a surgeon inserts the needle into the tissue, he/she tries to manipulate the needle body to steer it through a static or dynamic path to reach a specified target; the static and dynamic paths refer to offline and online path planning approaches respectively. Mostly, the needle steering doesn't happen easily, since there is still no exact, real-time and comprehensive displacement-force feedback from the areas of interest, due to inherent properties of minimally invasive surgeries [4]. On the other hand, tissue penetration causes some undesired events; e.g. target repositioning [2], obstacle reshaping and tissue over-stretching. That is, even if there is a rich visual feedback and its corresponding force data in a haptic system, the needle may not reach the preset target. Thus, surgeons need to use realistic simulators to be deeply trained on how to control, stabilize and steer the needle inside the tissue [5] using a pre-planned and trackable path (i.e. feasible for the needle to adapt its body with the path).

Obviously a much better approach is to replace humankind with a robot to intelligently and precisely manipulate the needle body (e.g. needle's base [2]). Such a robot should be highly trained to recognize tissue characteristics (e.g. brain tissue [6]), needle-tissue interactions [7] and also force-displacement and force-velocity relationships [1].

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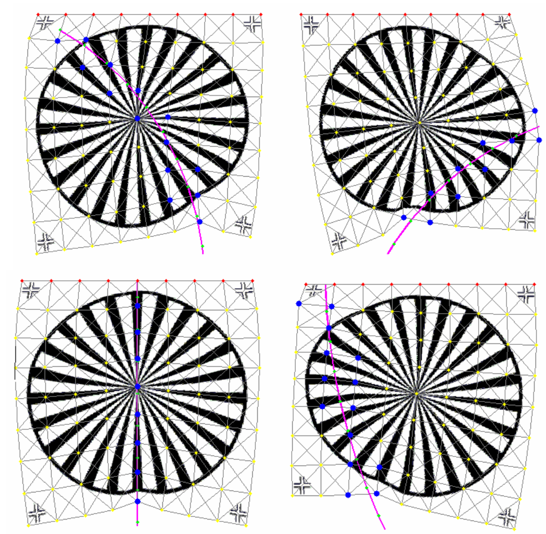

Fig. 1. Four instants of tissue deformation penetrated by the flexible bevel-tip needle, generated by the proposed model of the swine's brain tissue.

Due to unpredictable events during a needle-based surgery, like uncertain bleeding of penetrated tissues, the robot must be able to dynamically re-plan and correct the preset trajectory and change it to a safer path.

Although due to asymmetry of tip of steerable needles, a purely straight route for such needles (specifically those used for injection) seems impossible, some have proposed solutions to control the amount of needle deflection to avoid critical obstacles [3]. As an example, bones can not be penetrated by the needle's tip. Also sensitive nerves and vessels should not be hit by the needle body. Therefore the needles should be able to maneuver around obstacles. In this paper, a new fuzzy controller has been proposed for a robot manipulator with two degrees of freedom to steer the needle in obstacle-free and target-tracking paths.

The reminder of this paper is organized as follows. Section II reviews the related works. Section III describes a flexible needle model coupled with the tissue model and how to design an appropriate fuzzy controller for the needle manipulator. The simulation results of the needle steering in a virtual reality-based environment are illustrated in Section IV and finally, Section V summarizes our conclusions.

## II. RELATED WORKS

Relationship between the needle displacement and the corresponding forces during the penetration is used in needle-tissue simulators, preoperative planning and robotic surgeries [1]. To provide essential data for needle-tissue simulators and surgical robots, there is usually an instrumented needle to measure applied forces [1] while concurrently, tissue deformation is scanned via an imaging method [8]. Then, the acquired data will be used to formulate either linear [8] (due to tissue elasticity) or non-linear [9] (due to tissue viscosity) relationships between the applied forces and the tissue displacements. Such a formula, used as an interpolator, enables the simulator to estimate the real response of live tissues in different conditions. For example, DiMaio and Salcudean [2] developed a planar robotic manipulator with 3 degrees of freedom to drive a rigid and symmetric needle into a thin and elastic tissue phantom. Applied forces and tissue displacements were sampled during needle insertion to be used for linear model identification. The needle asymmetry, tissue viscosity, tissue non-homogeneity, needle deflection and force-velocity relationship were neglected in that work.

Although inherent tendency of bevel-tip needles to be deflected due to tip asymmetry during a penetration may be problematic, but as presented in [5], [10], [11], if surgeons/robots can control the amount of deflection, then the needle deflection will be helpful in steering the needle around the obstacles to perfectly reach those targets which have not been accessible previously by other needles [3]. Hence, some researchers [12] have proposed new kinds of well-steerable needles whose tips are bevel with a large effective cross-section with a thin and flexible body.

Different strategies for modeling and control of bevel-tip needles have been proposed [1], [3], [12]. In [12], the authors presented an interesting technique for proportional control of curved paths via various duty-cycled spinning of the needle.

In [2], the insertion of symmetric-tip needles into deformable tissues in addition to lateral motions of the needles are formulated as a trajectory planning and control problem by Jacobian matrix which mathematically relates the needle's base and tip. Also, Romano *et al.* [10] developed a pioneer work to steer bevel-tip needles in phantom by a teleoperation system.

Our proposed technique has exploited a fuzzy control approach for needle steering procedures, illustrated in Fig. 2. Although in this approach we have used the tip position feedback, the other feedbacks depicted in this figure are going to appear in a forth coming paper by the authors.

## III. MODELING AND DESIGN OF CONTROLLER

### *A. Tissue Modeling*

In order to increase the simulation speed, we propose to consider only the steady state equations of node displacements, meaning that the transient state is neglected to decrease the time needed for model updating. The technique of interest for tissue modeling is using a spring-network [13]. The main pattern contains six springs repeated in the network. Spring's constants are determined according to tissue properties extracted from an in-vitro experimental setup by uniaxial tension of swine's brain tissue [6].

A bevel-tip needle follows an uncertain curvature in a real tissue due to the uncertain non-homogeneity of the tissue. Also, the tip angle, amount of forces applied on the needle's base [14] and/or velocity of the needle insertion [2] are critically important and determinative in the amount of deflection of the needle's shaft during the steering.

In the proposed tissue model, different linear spring's constants are randomly distributed over the tissue network in order to model the non-homogeneity and uncertainty. Thus, this model is linear due to the linear springs and also is non-homogenous and uncertain due to the random distribution of spring's constants. Consequently, a bevel-tip needle inserted into the proposed tissue model certainly will not follow a constant curvature (similar to what happens in real tissues).

In Fig. 1, four samples of tissue deformation are simulated, each of which is different from the others in several aspects: 1) insertion angle, 2) insertion point, 3) friction between the tissue and needle body during the penetration, 4) penetration force, 5) length of the needle inserted into the tissue, 6) inherent bevel angle of needle's tip, and 7) tissue elasticity due to different random

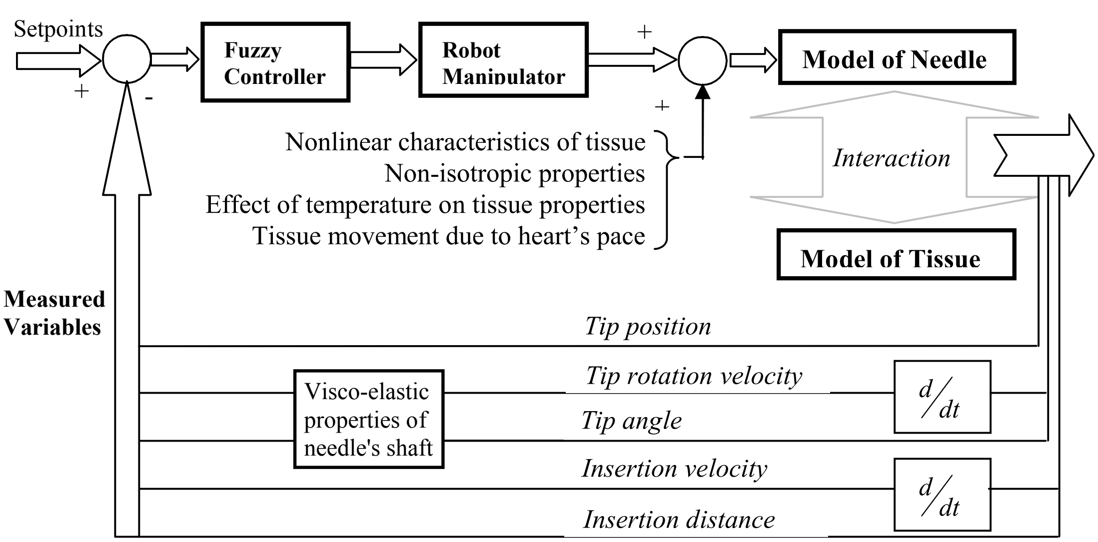


Fig. 2. The general block diagram for the robotic control and steering of surgical needles with bevel tip and flexible body inside soft tissues.

distributions of spring's constants.

The processor used to update the network with 9 x 9 nodes is the standard 2.21 GHz CPU with 0.5 GB of RAM which is an ordinary and non-expensive computer processor.

### *B. Design of Fuzzy Controller*

In this section, we are proposing a closed-loop system for fuzzy control of the needle in the tissue. We believe that the control system must have a closed-loop structure because, as shown in Fig. 2, the system may be interrupted by some known and unknown and even unpredictable disturbances. These disturbances may be unmodeled properties of real tissues and also can be a presentation of the errors that a robot may have due to non-linear characteristics of its motors which insert and rotate the needle. Changes in tissue properties due to different temperatures in different parts of human's body and also due to different body's temperatures in different people, also the effect of heart's pace in undesired movements of organs (which have not been studied in literature yet) in addition to the noise of imaging devices, all may be considered as disturbances influencing the performance of the surgery and consequently leading to a necessary need for a closed-loop control approach.

As mentioned, a bevel-tip needle inherently tends to deflect in the tissue, even if a purely-vertical force is applied on its base. This inherent deflectablity may seem to be a disadvantage and hence, there are some works (e.g. [2]) in which the needle's tip asymmetry is neglected, probably to simplify the model. On the other hand, it is also suggested to spin the needle's shaft during the insertion into the tissue to force the needle to move in a straight path; while if the spinning is stopped, the needle will follow a curvature due to its bevel angle. Any spinning between these two limits (i.e. with and without spinning) will generate a new curvature between the straight path and the original/primary curvature. In this way, different curvatures can be achieved by different spinnings. Thus, the manipulator controls the shaft spinning. Longer "stop" intervals create a steeper curvature of the needle, while longer "spin" intervals create a straighter trajectory. This technique is presented in [12], but without a preset and exact trajectory planning/tracking. They insert the needle manually to achieve the target in an obstacle-free path, but there is not a specific and previously-planned path for the needle to follow. In this regard, our proposed fuzzy controller precisely guides the bevel-tip needle to reach the target in the preset trajectory. The fuzzy controller is used due to tissue uncertainty [15], because this controller doesn't need comprehensive data and is able to control a system without having a precise model of the system.

The fuzzy controller receives the Cartesian coordinates of the actual/current position of the needle's tip, (x, y), and compares it to the *n* steps ahead of the deformed version of the preset path. The simulation tests show that an optimal value for *n* is 10, since if *n* is less than 10, the prediction will be weak, while when it is greater than 10, the error path increases. The controller compares the *ten steps ahead of the preset trajectory* in order to predict the future deformation of the path. In addition, it compares the position of the needle's tip with the *deformed path* (not the original path), since the needle motions deform the tissue and thus, the preset path should be deformed to adapt itself with the new structure of the network. Therefore, the controller compares the needle's tip position with the *deformed* and *future* figure of the planned path.

The proposed fuzzy controller is configured in the following way: i) singleton fuzzification, ii) 5 triangular membership functions, iii) COG defuzzification, and iv) Mamadani rule of inference, using MaxMin{} operators. Now, the controller output is the calculated spinning, based on the if-then rules used as the rules of the fuzzy controller presented below:

```
If(Needle is okay)
         then (Reff has no-change)
If(Needle is less-Right)AND(Bevel is 180)
         then (Reff has less-Inc)
If(Needle is Right)AND(Bevel is 180)
         then (Reff has Inc)
If(Needle is less-Left)AND(Bevel is 180)
  then (Reff has less-Dec)
If(Needle is Left)AND(Bevel is 180)
         then (Reff has Dec)
If(Needle is less-Right)AND(Bevel is -180)
         then (Reff has less-Dec)
If(Needle is Right) AND (Bevel is -180)
         then (Reff has Dec)
If(Needle is less-Left)AND(Bevel is -180)
         then (Reff has less-Inc)
If(Needle is Left) AND (Bevel is -180)
         then (Reff has Inc)
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where *Inc*, *Dec* and *Reff* stand for Increasing in radius, Decreasing in radius and Effective Radius, respectively. *Reff*, effective radius, refers to the radius of curvature obtained by a specific needle spinning. A simple method concurrently determines the bevel-right or the bevel-left tip.

## IV. SIMULATION RESULTS

Figure 3 shows four samples, selected from more than 20 different tests of needle steering in the virtual reality-based environment that artificially simulates the real tissue of the swine's brain to provide the data needed for the feedback in the closed-loop system. As expected, in Fig. 3 the needle matches its body with the preset trajectories by a number of feasible maneuvers. Pink and green lines correspond to the needle body and the deformed preset path respectively, and also the blue nodes show those nodes which are in direct contact with the needle and receive penetration forces. In each sample, one of tissue's edges is rigidly fixed shown with red nodes.

Table 1 compares the four needle steering simulated in the Fig. 3. The table shows that, although the simulations are different in several aspects (e.g. insertion point, insertion angle, bevel angle and insertion error), but the fuzzy controller is able to generate the appropriate commands to eventually make the needle body adapted with the planned path, while the tissue is *uncertain* and hence, the needle may not exactly follow a specific and constant curvature.

Another important note, illustrated in Fig. 3 and Table 1, is the ability of the controller to compensate the insertion error, since this error is one of the most critical errors in clinical applications of needle surgeries. In this regard, in the four simulations, the insertion error is set to be +1.3, -0.4,

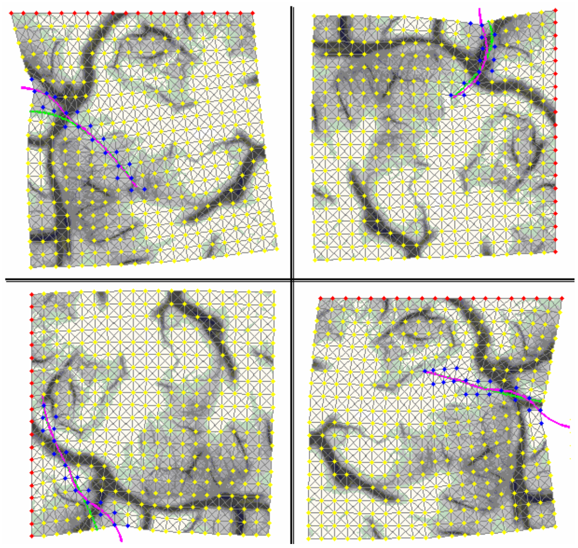

Fig. 3. The fuzzy controller guides the needle in the artificial tissue of the swine's brain to follow the desired trajectories. The pink and green lines correspond to the needle and the deformed planned path respectively. The blue nodes are in direct contact with the needle and receive penetration forces. The red nodes are rigidly fixed.

+1.6 and -1, respectively; but the targeting accuracy is evidently zero in all cases. It is important to mention that although the main concern in needle steering procedures is to minimize the targeting error, other parameters are also determinative, one of which is path length which should be minimized too. Actually, this is an optimization problem that we have pursued separately in another work presented in [16].

## V. CONCLUSION

In this study, we utilized a non-homogenous and uncertain spring network to model a reality-based artificial brain tissue based on biological data extracted from an experimental setup. This approach helps us provide sufficient data for the tip position feedback. The controller has a fuzzy structure in order to overcome unmodeled events and also to damp disturbances. This arrangement steers the needle in the deformed trajectory to reliably hit the target. The algorithm is able to control the needle in dynamic paths, meaning that if unexpected obstacles are found, the planner will change the path.

In tissue modeling, our approach has some advantages. The tissue network is fast-updatable and consequently allows the processor to update all the nodes in tissue animation even in high needle velocities. Another advantage of the proposed method is that the model explicitly considers the effect of uncertainty and non-homogeneity during the needle steering.

In the needle steering problem, path-following by the needle in uncertain tissue, based on a predictive algorithm, is a new method accomplished in this paper. The setpoint of the closed-loop system changes in each update frequency due to non-homogenous deformation of the tissue. This is an intelligent robotic control approach to decrease the error of the needle steering in a real deformable tissue, while in similar works [12] the needle is manually manipulated to maneuver around the obstacles without an exact path.

## VI. FUTURE WORKS

The setpoint of the control system is a path for guiding the needle on it. This path should be determined by a path optimization algorithm. In this regard, we proposed a 2D path planning approach in [16] to generate the setpoint (i.e. input) of the control system. Also the tissue modeling approach used in the current work, is extensively described in [13]. As one of the future works, we intend to extend our method of tissue modeling, path planning and needle steering to a 3D environment in a haptic framework. The next step is to manufacture a haptic-robotic hardware system to practically execute the proposed algorithms on a phantom.

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