CIS II Seminar Paper Review
Robotic Insertion of Flexible Needle in Deformable Structures Using Inverse Finite-Element Simulation

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1 Review of Project Aim

This project focuses on simulating a commonly practiced local needle trajectory adjustment technique during freehand needle insertions, and evaluating a proposed interaction model to see if it is suitable to be extended into a trajectory generation and tracking problem in control.

2 Paper Positioning and Aim

This paper points out that, during flexible needle insertions, both the soft tissues and the needle deform, therefore the pre-planned trajectory is also displaced during the insertion process. Traditional controllers that have been used for needle steering purposes face some drawbacks, specifically, they depend on high resolution per-operative images, which is difficult to come by at a very high frequency. Segmentation of the needle and structures is also time consuming, which presents challenge in terms of control implementation. In addition, these methods can only act on the error after it's been detected – in other words, these controllers cannot predict the error themselves because they do not have the biomechanical model of the tissue. Finally, large deformations can significantly alter the control law.

The main goal of this paper is to demonstrate that a complex nonlinear interaction model solvable by finite element method can be extended to build control laws, and overcome some of the drawbacks of the aforementioned servoing methods.

3 Key Result and Relevance

A key result from this paper is an experimental verification of their approach by controlling a 6 degree-of-freedom (DOF) articulated robot arm to insert a flexible needle into a soft, deformable foam. This process is assisted by real-time calculation of their proposed finite-element model based on live image feedback. They reported an average tracking error of 1.62mm and a maximum error of 3.73mm along the trajectory. The reported computation frequency is approximately 100Hz for robot control commands. The relevance of this paper lies in the fact the controls based initially on finite element formulation can be feasible. The authors also provided high level algebraic derivations, outlining the steps necessary to develop control strategies that are based on finite element formulations.

4 Finite Element Modelling and Constraint Formulations

The authors modeled the flexible needle as a set of linked beams. Each beam consists of two nodes, and each node has a total of six DOFs, including position and orientation. The deformable foam model is obtained 3D segmentation, and is discritized using linear tetrahedral elements. THey formulated the co-rotational elastic forces of a typical element, and use these forces in a global sense to counter the constraint forces, which are added to the global governing equation by Lagrange multipliers.

For the constraints, the authors proposed four constraints:

- Bilateral constraint: fixes the needle base to the robot end effector
- Penetration constraint: when the needle tip first contacts the form
- Sliding constraint: after penetration, prevents the needle from going laterally
- Observation constraint: used to track the optical markers and register the FE model using non-rigid registration

For the control law, an objective function is proposed to minimize the needle tip distance to the pre-planned trajectory, as well as the angle between the needle and trajectory tangent. A linearization step is performed to derive the Jacobian of Simulation, which relates the instantaneous robot base motion to the motion at the needle tip.

5 Paper Evaluation

Overall, the high level abstractions in the derivations help establishing an outline for mathematical development, but many are used without a proper explanation, making some of their choices seem rather arbitrary.

Technically, the authors constructed a very elaborate experiment setup to prove the viability of their proposed method. However, their experiment “sandbox” does not correspond to realistic surgical scenarios, where medical image acquisition and analysis remains a key hurdle to real time robot control. By having high speed cameras tracking fiducial markers that are placed along the depth direction of needle insertion cleverly circumvented the above issue, yet the generalizability of their proposed method also diminishes as a result.

6 Reference

Y. Adagolodjo, L. Goffin, M. De Mathelin and H. Courtecuisse, ”Robotic Insertion of Flexible Needle in Deformable Structures Using Inverse Finite-Element Simulation,” in IEEE Transactions on Robotics, vol. 35, no. 3, pp. 697-708, June 2019, doi: 10.1109/TRO.2019.2897858.