Robotic Insertion of Flexible Needle in Deformable Structures Using Inverse Finite-Element Simulation

Yinoussa Adagolodjo, Laurent Goffin, Michel De Mathelin, and Hadrien Coutecuisse

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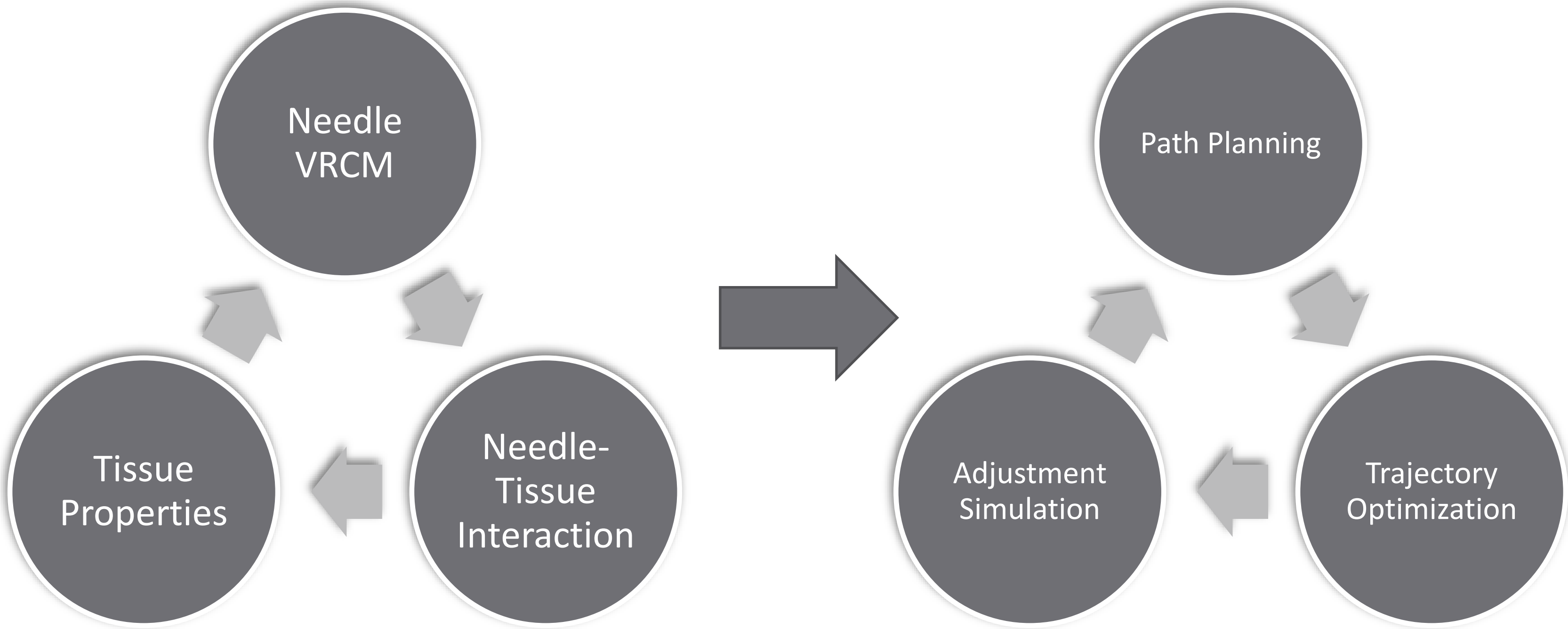
Project Summary and Review

- **Design and create experiment setup to mimic and capture this needle VRCM**
- **Evaluate the accuracy of proposed needle-tissue interaction model**
- **Implement path planning algorithms to generate optimal needle base motion**



Paper Selection

IEEE TRANSACTIONS ON ROBOTICS, VOL. 35, NO. 3, JUNE 2019 697

Robotic Insertion of Flexible Needle in Deformable Structures Using Inverse Finite-Element Simulation

Yinoussa Adagolodjo, Laurent Goffin, Michel De Mathelin, and Hadrien Courtecuisse

- A constraint-based interaction model for simulation of needle insertion and complex nonlinear phenomena
- A numerical approach to calculate the *Jacobian of Simulation* in the constraint space for fast estimation of the Jacobian
- A method to bridge finite element (FE) simulation and control for trajectory tracking under large tissue and needle deformation

Relevance to this project:

A high-level walk-through of the formulations taken to bridge a (forward) finite element simulation with control to allow trajectory tracking, combined with image-to-material correlations to estimate/generate large material deformations.

Problem Statement

- During flexible needle insertions, both the soft tissues and the needle deform, resulting in a displacement of the trajectory and the target specified during preoperative planning

- Traditional controllers that serve to correct needle path via *visual-servoing*:
  1. Depends on high-resolution per-operative images, which is difficult to come by
  2. Can only act on the error after the fact, i.e. cannot predict the error due to lack of biomechanical models
  3. Cannot account for change in control model due to large tissue deformation

- Goal: to demonstrate a finite-element based closed-loop controller that can drive a flexible needle to follow a pre-defined trajectory in the event of large deformations during the insertion process

Key Results

- Demonstrated the proposed control law by controlling a 6-degree-of-freedom (DOF) articulated robot arm to drive a $21\text{G} \times 12cm$ needle into a flexible foam, with real-time calculation of FE model that accounts for deformation of the foam with live images.
- High trajectory tracking accuracy with average tracking error of $1.62mm$ and maximum error of $3.73mm$.
- High computational speed ($\sim 93Hz$) by minimizing the number of repeated calculations and via GPU parallelization.

Significance

- Demonstrated the feasibilities and challenges of FE based control law and implementation

Technical Approach: FE Models

- A Timoshenko formulation that models the flexible needle as a set of linked beams, with each beam consisting of two nodes and each node having 6 DOFs (position and orientation)

$$\mathbf{K}_{ne} = \int_{V_{ne}} \left(\mathbf{C}_{ne}^{T}\, \mathbf{D}_{ne}\, \mathbf{C}_{ne}\, dV_{ne}\right)$$

- A tetrahedral element mesh of the material obtained from 3D segmentation before needle insertion, where each element has four nodes with 3 DOFs

$$\mathbf{K}_{ve} = \int_{V_{ve}} \left(\mathbf{C}_{ve}^{T}\, \mathbf{D}_{ve}\, \mathbf{C}_{ve}\, dV_{ve}\right)$$

- Co-rotational elastic forces of an element (beam or tetrahedral)

$$\mathbf{f}_e = \mathbf{R}_e \mathbf{K}_e \left(\mathbf{R}_e^{T} \bar{\mathbf{p}}_e - \mathbf{p}_e\right)$$

- Governing equation with constraints added by Lagrange multipliers

$$\mathcal{F}(\mathbf{u}) + \mathcal{H}(\mathbf{p}_n, \mathbf{p}_v, \mathcal{X}, \mathbf{m})\boldsymbol{\lambda} = \mathbf{0}, \text{ with } \quad \mathbf{u} = \begin{pmatrix} \mathbf{p}_n \\ \mathbf{p}_v \end{pmatrix}$$

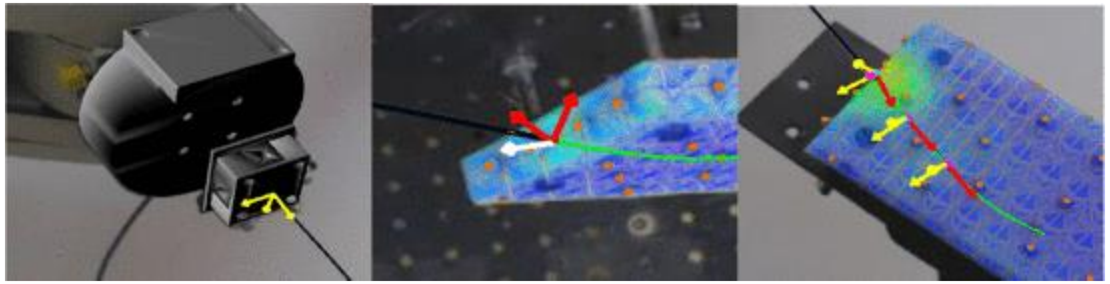
Technical Approach: FE Models + Constraints

a) *Bilateral constraints* $\mathcal{H}_X(p_n, X)$: fix needle base position to robot end-effector

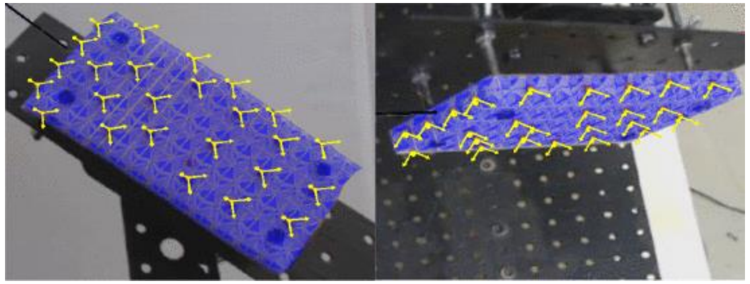
b) *Penetration constraint* $\mathcal{H}_\Phi(p_n, p_v)$: applied before needle penetration

c) *Sliding constraint* $\mathcal{H}_\Psi(p_n, p_v)$: applied after needle penetration and during insertion

d) *Observation* $\mathcal{H}_\Omega(p_v, m)$: track optical markers and perform non-rigid registration



a) b) c)

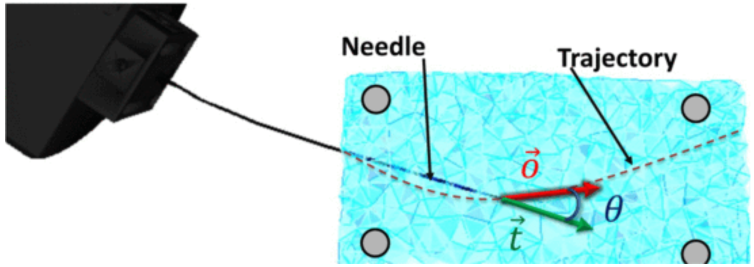


d)

Technical Approach: Control Models

- Objective function to minimize error between needle tip position and the trajectory, as well as the angle between tangents of needle and trajectory curves at each time frame

$$\mathbf{E}(\mathcal{X}, \mathbf{p}_n, \mathbf{p}_v, \mathbf{m}) = \begin{pmatrix} \mathbf{n} - \mathbf{t} \\ \eta\,\theta \end{pmatrix} = \mathbf{0}$$



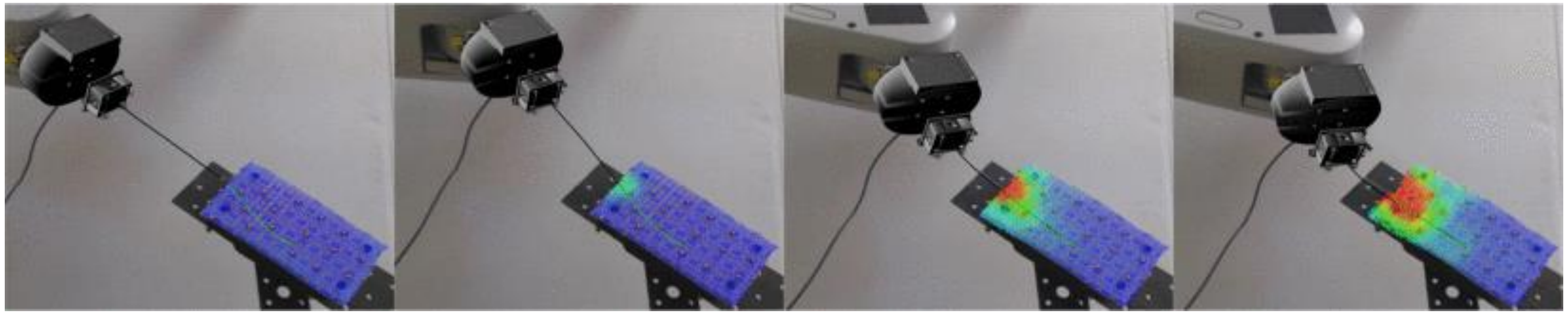
- Linearization of the objective function and formulation of the *Jacobian of Simulation*

$$\mathbf{E}(\mathcal{X}^{(t)}, \mathbf{p}_n^{(t)}, \mathbf{p}_v^{(t)}, \mathbf{m}^{(t)}) + \frac{\partial \mathbf{E}}{\partial \mathcal{X}} d\mathcal{X} = \mathbf{0}$$
$$\Rightarrow d\mathcal{X} = \mathbf{J}^{-1}\mathbf{E}(\mathcal{X}^{(t)}, \mathbf{p}_n^{(t)}, \mathbf{p}_v^{(t)}, \mathbf{m}^{(t)})$$

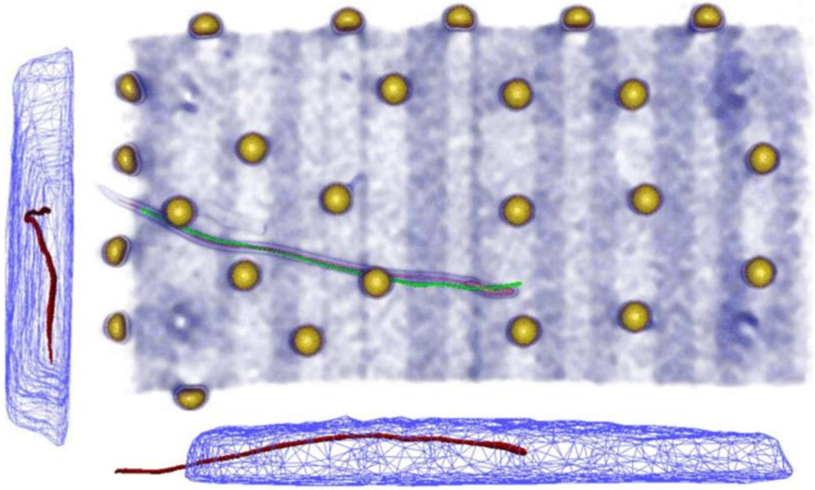
- Explicit calculation of columns of the Jacobian

$$\mathbf{J}[:i] = \frac{\mathbf{E}(\mathcal{X}^{(t)}, \mathbf{p}_n^{(t)}, \mathbf{p}_v^{(t)}, \mathbf{m}^{(t)}) - \mathbf{E}(\mathcal{X}^{(t)} + \delta\mathcal{X}_i, \mathbf{p}_n^{(t)}, \mathbf{p}_v^{(t)}, \mathbf{m}^{(t)})}{\|\delta\mathcal{X}_i\|}$$

Results



A live AR overlay of the robot end-effector and the flexible needle, along with Von Mises stress field of the deformed foam.



A CT confirmation of the actual needle trajectory (red) versus the planned trajectory (green)

Process	min(ms)	mean(ms)	max(ms)	time%
FM	2.26	2.95	4.76	25.62
CD	0.19	0.22	0.34	1.91
CC	2.46	2.61	3.18	22.67
SC(×7)	4.29	4.84	6.72	42.07

Computation time and percentage of main simulation steps. FM: Free motion; CD: Constraint definition; CC: Compliance computation; and SC: Solve constraints.

Paper Assessment

- Overall presentation:
  - Pros:
    1. high lever abstraction makes derivations of presented models easier to follow
    2. plenty of figures to justify their formulations and to show experiment setup
  - Cons:
    1. no explicit formulation of key FE model
    2. no justification of specific choices of computational method, makes some of their methods appear arbitrary
- Technical approach:
  - Pros:
    1. an elaborate experiment setup to provide highly accurate real-time tracking of the entire system
  - Cons:
    1. a “flat” insertion where the deformation of the foam can be tracked entirely by cameras: not realistic in real clinical scenarios

Conclusion and Lessons Learned

- FE formulations can indeed be translated into control laws, but significant computational resources can be taken by solving these models even with highly sophisticated methods
- Significant gap still exists to bring live medical images into this control methodology, which relies heavily on live tracking of the displacement field of the material
- Displacement of the trajectory itself needs to be considered during needle insertion

References and Q&A

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