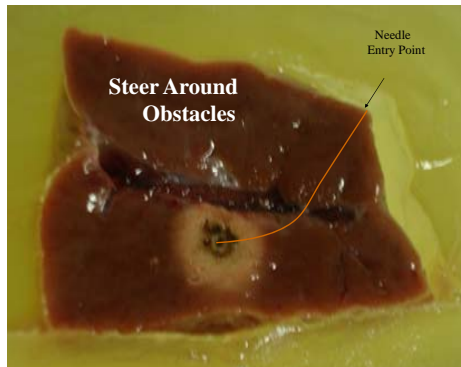


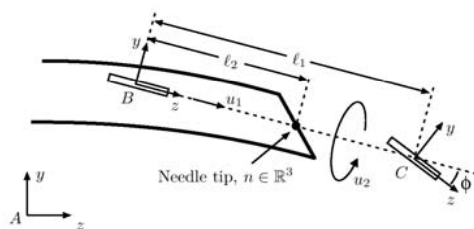
Introduction

- Objective: control a bevel-steered needle along a general 3D trajectory.
- Useful for avoiding obstacles and compensating unmodeled disturbances



Hypothetical Example: A slice of liver with simulated tumor. Major vessels are among the possible obstacles for steerable needles.

Model



Apply the nonholonomic model of [1]

$$V_1 = [0 \ 0 \ 1 \ \kappa \ 0 \ 0]^T \quad V_2 = [0 \ 0 \ 0 \ 0 \ 0 \ 1]^T$$

$$g_{ab}^{-1}(t)\dot{g}_{ab}(t) = u_1\hat{V}_1 + u_2\hat{V}_2, \quad n(t) = p_{ab}(t)$$

With the fixed angle coordinates of [2]

$$\dot{X} = [\dot{x} \ \dot{y} \ \dot{z} \ \dot{\alpha} \ \dot{\beta} \ \dot{\gamma}]^T$$

$$\dot{X} = F(\alpha, \beta, \gamma) [u_1 \ u_2]^T$$

Controller

Implement input-output feedback linearization to obtain:

$$V' = [\ddot{x} \ \ddot{y} \ \ddot{z}]^T = A(X, u_1) [\ddot{u}_1 \ \ddot{u}_2]^T + B(X, u_1, \dot{u}_1)$$

Control Law:

$$V = [\ddot{x}_d \ \ddot{y}_d \ \ddot{z}_d]^T + K_a \ddot{e} + K_v \dot{e} + K_p e$$

To determine inputs, cast as an optimization problem:

$$\min_{\ddot{u}_1, \ddot{u}_2} \|V - V'\|$$

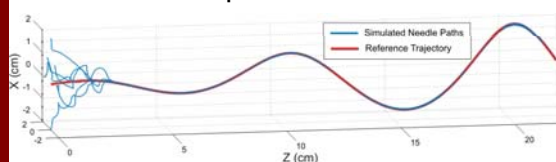
Note: it is also possible to add actuator constraints within this minimization

Solving via least squares yields:

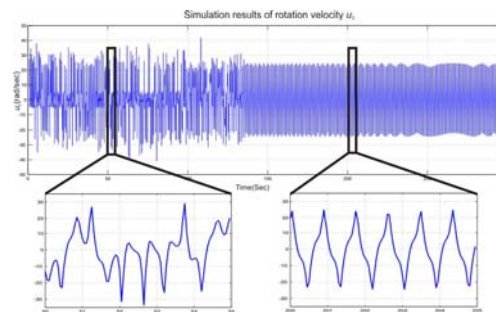
$$[\ddot{u}_1 \ \ddot{u}_2]^T = A^\dagger (V - B)$$

Simulation Results

Controller implemented in Simulink



(Above) Several simulated needle insertions with differing initial conditions converge to the reference trajectory - a helix with increasing diameter. (Below) Rotation velocity vs. time for a single insertion



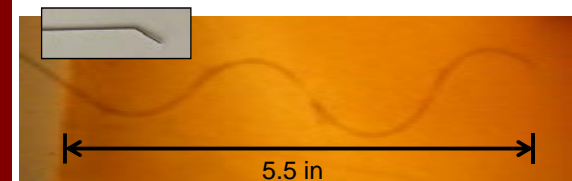
New Actuation Unit Design



- Can insert multi-lumen needles or active cannulas
- Straightforward to add lumens
- Minimizes the distance between robot grip point and body entry point
- Hardware under construction



Experiment



Preliminary experiments with "kinked" bevel tip needles appear to provide sufficient curvature for control

Citations

- [1] R. J. Webster III, J. S. Kim, N. J. Cowan, G. S. Chirikjian, and A. M. Okamura. *Nonholonomic Modeling of Needle Steering*. Int'l. J. Rob. Res. 25(5-6), 509-525, 2006.
- [2] V. Kallem, and N. J. Cowan. *Image-Guided Control of Flexible Bevel-Tip Needles*. IEEE ICRA, 2007.