Active Cannulas: Applications to Steerable Needles

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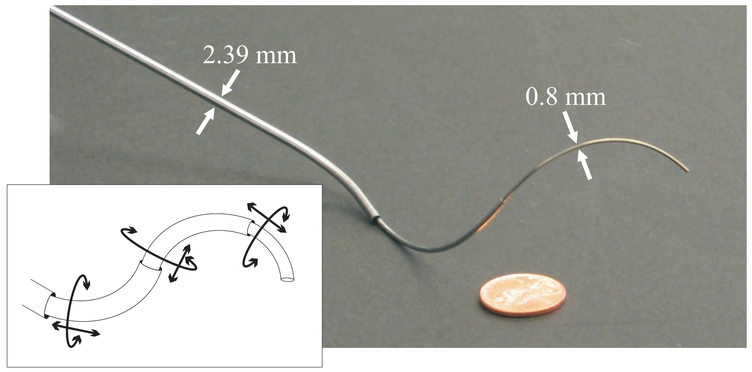
Introduction

Active cannulas [1] are a complement to steerable needles in performing dexterous medical interventions in or around constrained environments. Active cannulas can act as a delivery mechanism for steerable needles, traversing the open areas en route to the eventual subsurface target.



The study of cannulas can also provide insight into how a pre-bent needle will interact with an existing channel in the tissue when rotating the needle at its base.

Differential Kinematics of Concentric Nitinol Tubes [2]

Concentric tubes with straight transmission sections and a constant curvature section at the distal end will have a resulting shape consisting of piecewise planar arcs. The corresponding rigid body transformation can be written as a composite function: a map from joint variables to arc parameters and a map from arc parameters to $\mathrm{SE}(3)$, and expressed as a product of exponentials involving these arc parameters:

$$g = g_0 g_1 \cdots g_m, \quad g_j = e^{\widehat{\mathbf{e}}_6 \Delta\phi_j} e^{(\widehat{\mathbf{e}}_3 + \widehat{\mathbf{e}}_4 \kappa_j)\ell_j}, \quad j = 1, 2, \ldots, m,$$

The map from joint variables to arc parameters requires finding a local minimum in the stored elastic energy, U, of all interacting tubes. That is, we find where the gradient, ∇U, of the energy function with respect to a set of unknown "free" variables, $\boldsymbol{\psi}$, is zero, and then ensure the Hessian, $D^2_{\psi} U$, is positive definite. These variables ψ correspond to the angles of the tubes at the end of the long straight transmission.

To compute the Jacobian, we use the fact that $F(\boldsymbol{\psi}, \boldsymbol{q}) = \nabla_{\boldsymbol{\psi}} U = 0$ is an implicit function between the free variables, $\boldsymbol{\psi}$, over which the energy was minimized, and the joint variables, $\boldsymbol{q}$, which act as the system inputs. The remainder of the computation is straight forward [2], and results in

$$V^s_{st} = \left(\dot{g} g^{-1}\right)^{\vee} = J^s_{st} \dot{\boldsymbol{q}}$$

where V^s_{st} is the linear and angular velocities in the spatial frame, J^s_{st} is the spatial Jacobian, and $\dot{\boldsymbol{q}}$ represents the joint velocities.

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Visual Servo Controller [2]

Given the spatial Jacobian, we wish to control the inputs, $\boldsymbol{q}$ to the concentric tubes to drive the tip position $\boldsymbol{p} \in \mathbb{R}^3$ to a desired location under visual feedback. Note that

$$\dot{g} = \begin{bmatrix} \dot{R} & \dot{\boldsymbol{p}} \\ 0 & 0 \end{bmatrix} = \widehat{V}^s_{st} g \implies \dot{\boldsymbol{p}} = \boldsymbol{\omega}^s_{st} \times \boldsymbol{p} + \boldsymbol{v}^s_{st} = \begin{bmatrix} I_{3\times3} & -\hat{\boldsymbol{p}} \end{bmatrix} V^s_{st}.$$

Let $J_v, J_\omega \in \mathbb{R}^{3\times(2n)}$ represent the linear and rotational components of the spatial Jacobian, such that

$$\dot{\boldsymbol{p}} = \begin{bmatrix} I_{3\times3} & -\hat{\boldsymbol{p}} \end{bmatrix} \begin{bmatrix} J_v \\ J_\omega \end{bmatrix} \dot{\boldsymbol{q}} = J_p \dot{\boldsymbol{q}},$$

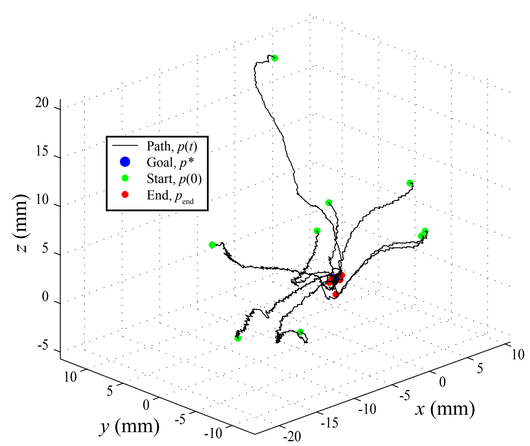
Then, we have

$$\dot{\boldsymbol{q}} = -J_p^{\dagger} K(\boldsymbol{p} - \boldsymbol{p}^*).$$

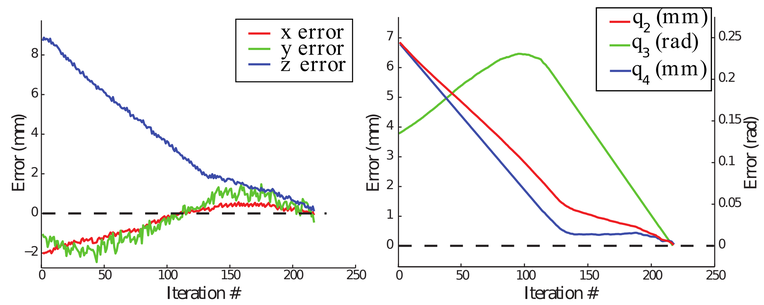
In general, n tubes will provide $2n$ degrees of freedom and the Jacobian relating velocities in a chosen world frame of reference will be $J_p \in \mathbb{R}^{6\times(2n)}$. As such, the choice of pseudo-inverse can be tailored to meet constraints imposed by the task.

Experimental Results

In these experiments, we implement a position-based visual servo controller. We neglect the orientation at the cannula tip, and thus only actuate three degrees of freedom such that the Jacobian J_p, as discussed above, is square and invertible.

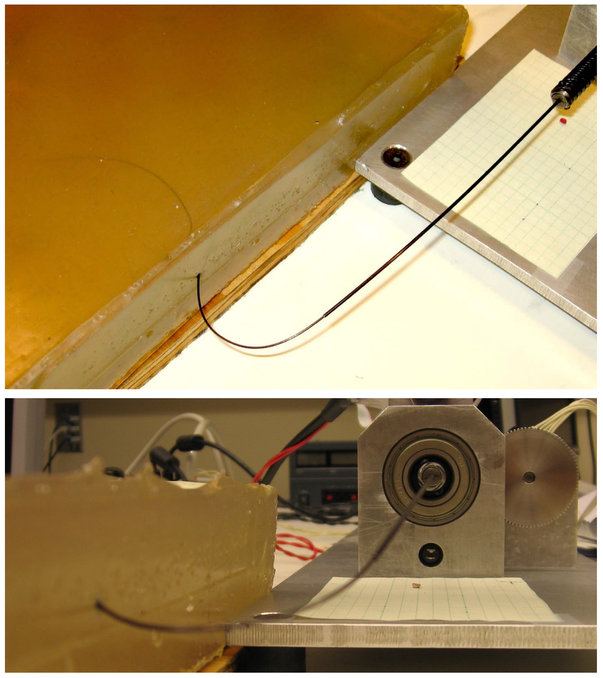


Experimental trials - Initial displacement: 8.80-21.76 mm Final error: 1.543 mm maximum, 0.674 mm average



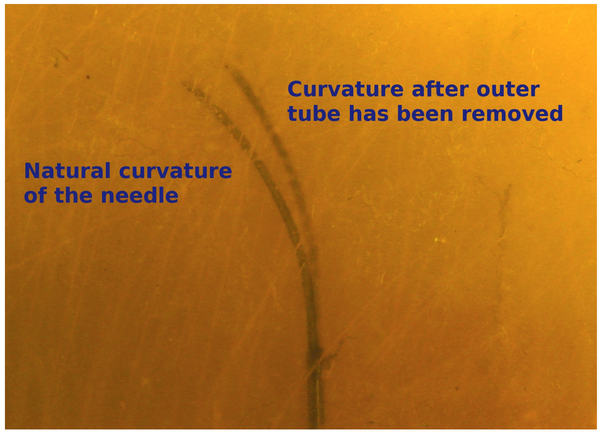
The left image shows convergence in each axis of the 3D position of the cannula tip. The right image shows the error between the joint variables and their values at the goal position goes to zero as the cannula tip converges to the goal locations in the image planes.

Delivering Needles Through Cannulas



Active cannulas can provide a method of delivering steerable needles to hard to reach locations by dexterously traversing intermediate open areas. Shown here is a mock anecdote of the desired synergy between cannulas and a steerable needle, where the cannula steers in free space to the tissue, and the needle is inserted from the end of the cannula into the tissue.

Tissue Acts As an "Outer Cannula"



We examine the interaction of a curved needle and a straight channel in the tissue. The resulting shape of the needle will provide insight into how we can treat existing tissue channels as an outer cannula and characterize its elastic properties.

Citations

[1] Robert J. Webster III, Joseph M. Romano, and Noah J. Cowan. Mechanics of precurved-tube continuum robots.IEEE Trans. Robot.Accepted.
[2] Robert J. Webster III, John P. Swensen, Joe M. Romano, and Noah J. Cowan. Closed-Form Differential Kinematics for Concentric-Tube Continuum Robots with Application to Visual Servoing. International Symposium on Experimental Robotics, In Press, 2008.

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