Towards Closed Loop Control of a Continuum Robotic Manipulator for Medical Applications

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Flexible catheters used in wide array of diagnostic & interventional procedures
- Compliant structure protects soft tissue
- Access small anatomical volumes
- Navigate complex paths
- But – difficult to control manually
Background / motivation

- Tele-robotic implementations created to overcome drawbacks.
  - Greatly simplified catheter use – particularly in 3D volume applications
    - But – position/force control challenges due to:
      - Compliant structure
      - Internal friction
  - Results in non-intuitive control

- Interested in exploring use of catheter-based feedback

- Others exploring topic include Dupot, Simaan, Camarillo, Desai, Howe, ...
Catheter Control Testbed

**Master Workstation**
Visualization / GUI

- Force-reflecting master input/output device
- Haptic & visualization operator feedback

**Flexible Catheter and Slave Subsystem**

- Flexible catheter slave servomechanism
- Flexible (cable-driven) catheter

**Localization / Imaging / Sensing**

- Stereo Camera Localization
- Electromagnetic Localization
  - 6 dof sensors (4x)
  - EM transmitter & electronics

**System Controller**

- Eshed Scorpion ER01X robots
- Stereo cameras
Catheter Analog Manipulator

Catheter Analog:
- Construction jig (removed during use)
- Teflon spine
- Mesh outer sleeve

Catheter cross-section:
- Central lumen (EM sensor access)
- Pull wires (tendons) (4x)
- Tendon guide lumens (4x)

Teflon spine detail:
- Alternating flexures

(Fixed guide catheter not shown)
**Joint motion:**
- Telescoping extension
- Articulation (pitch & yaw)

**End-point position:**
- Closed-form forward / inversed kinematics
- Assumes constant curvature

**Joint space coordinates:**
\[ \alpha = \sqrt{\phi_p^2 + \phi_y^2} \]
\[ \theta = \tan^{-1}\left(\frac{\phi_p}{\phi_y}\right) \]

**End-point (task) coordinates:**
- \( X_C, Y_C, Z_C \)
Continuum Robotics Experimental System Test-bed:

- 11 DOF servomechanism test-bed
- High-bandwidth closed-loop control (relative to catheter dynamics)

Pull-wire actuation (pulley)

Telescoping extension

Roll-axis motion
Control Architecture - Open Loop

- Large deviations from desired trajectory
- Source: Model errors + friction

Tracking error (in-plane):

\[ \text{~25 mm error} \]
- EM 6-DOF sensor placed at end-point for position measurement
- Use constant $\kappa$ kinematics to obtain equivalent joint space error
- High-bandwidth (relative) of CREST allows simple integral controller
Closed loop control significantly improves command tracking capability.

Surprisingly, simple controller corrects for kinematic errors, cable stretch, and for friction (sometimes!)
Future Work - Model Based Control

- Much work to be done in regards to control
- Simple controller begins to breakdown for high articulation angles (friction becomes significant)
- Interested in model-based control approaches
Equations of motion:

\[ \dot{\mathbf{M}} \ddot{\mathbf{z}} + \mathbf{B} \dot{\mathbf{z}} + \mathbf{Kz} = \mathbf{F}_u + \mathbf{F}_\mu \]

\[ \ddot{\mathbf{z}} = \frac{1}{m_i} \begin{bmatrix} \mathbf{B} \mathbf{z} - \mathbf{Kz} + \mathbf{F}_u + \mathbf{F}_\mu \end{bmatrix} \]

(Linear approximation > diagonal mass matrix)

- Lumped parameter modeling approach
- Ignore Coriolis/centrifugal forces > linear, decoupled model
- Friction models easily incorporated
- 3D shape recovered using constant-\(\kappa\) assumption between mass elements

Transformation to 3D-space

\[ \mathbf{z} \rightarrow \mathbf{x} \]

Nonlinear friction model

\[ \mathbf{F}_\mu = \sum f_i (\mathbf{z}, \dot{\mathbf{z}}, \mathbf{u}, \dot{\mathbf{u}}) \]

Control inputs

\[ \mathbf{F}_u = \mathbf{B}_u \dot{\mathbf{u}} + \mathbf{K}_u \mathbf{u} \]
Future Work - Model Based Control

- When friction is considered – experimentally observed behaviors result
  - Hysteresis
  - Nonlinear instantaneous motion
- Constant curvature assumption breaks down

**Non-constant curvature:**

**Nonlinear motion:**

- Hysteresis
- Constant curvature assumption breaks down

**Catheter Analog (measured curvature)**

- **Curvature [1/cm]**
  - measured
  - model (with friction)
  - constant curvature

- **Arc-length [cm]**
  - initial catheter configuration
  - desired path
  - end-point velocity
  - start position
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