Redundantly Arranged Rigid Joints and Flexible Continua for Increased Continuum Manipulator Performance and Continued Safety

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On today’s tour

- Operating in the heart
- Interleaved Continuum-Rigid Manipulation
- Single degree-of-freedom (DOF) performance testbed
- Multi-DOF prototype
- Looking forward
The heart is important – and moving

- Everything is moving
- Each patient is unique
- Can’t suffer complications

youtube.com/watch?v=SZ-ulfj-hIQ

youtube.com/watch?v=HyQjpQf_eME

WISCONSIN Robotics + Intelligent Systems Lab

femoral vein

2008 Camarillo... Mechanics Modeling
Catheters are inherently safe ... and hysteretic

- Elastomer structure – similar bending stiffness to organs
- Highly hysteretic – presently, modeling is insufficient
Let’s complement catheters with rigid joints

Flexible continuum segments:
+ access large workspace
+ soft, atraumatic construction
- nonlinear hysteretic actuation and motion

Rigid link joints:
interleaved between flexible segments
+ small design, lie within flexible profile
+ linear compensator for flexible errors
- limited range of motion

Interleaved Continuum-Rigid Manipulation

The performance of rigid manipulators with the inherent safety of today’s catheters
A new concept, let’s be strategic

Desire increased

**Performance:**
- Increase accuracy, precision, & speed?
- Reduce or avoid hysteresis?

**Dexterity:**
- Expand the dexterous workspace?
- Maintain ‘good’ configurations?

...to enable
- Teleoperation
- Obstacle avoidance
- Avoidance of distal dynamics
- Target motion compensation
- Contact impedance managing
...among others

1D Performance Testbed

5D Actuation & Control Prototype
The performance testbed

- Controlling articulation ($\alpha$)
- Redundant catheter and rigid joint
- Tip pose tracked by emf
Error is partitioned by frequency
4x faster, same accuracy

\[ \alpha \]

\[ \alpha_F \]

\[ \alpha_R \]

Interleaved

Flexible-only

Estimated Flexible

Estimated Rigid

Interleaved

Maximum rigid joint motion

Time [s]

Articulation [°]

Time [s]

Articulation [°]
Why the overshoot?

- Two reasons:
  - Higher articulation leads to faster & larger flexible response for the same step-error
  - Rigid joint saturation due to shorter lever arm
- Results in decreased phase margin:
Desire increased

**Performance:**
- **Increase accuracy, precision, & speed?**
  - 4 times faster, same accuracy
- **CL fundamentally limited by first mode**
- **Reduce or avoid hysteresis?**
  - Fine resolution from rigid joint

**Dexterity:**
- Expand the dexterous workspace?
- Maintain ‘good’ configurations?

**Other takeaways:**
- Frequency partitioning attractive
  - challenging in multi-DOF
- Joint limits are important
- Plant dynamics change with articulation, decouple these?

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5D Actuation & Control Prototype
1D results encourage 5D prototype

- Towards a clinical manipulator, need to consider
  - Mechanical design for continued safety
  - Joint design for increased dexterity and error correction
  - Actuator/encoder selection for speed and accuracy
  - Transmission design
  - Control design to utilize above

- Also desire to expose unknown unknowns
  - The design questions are obvious, lacking in particulars
  - Prototypes are good for exposing assumptions and knowledge-gaps
A 5D clinically-approximate manipulator

Ex-vivo Drives

Vasculature Model

5 DOF Interleaved Manipulator
5D design – degrees of freedom

- 2 flexible segments
  - Proximal roll and catheter
- 2 rigid joints
  - Distal pitch and roll
  - Rigid joints 3D printed
- 1 virtual tip-to-target distance
- Redundancy varies with configuration
5D design – actuators and transmissions

- Remote actuation
  - Servos external to the patient

- Flexible transmissions safely navigate vasculature
  - 12mm Teflon proximal tube
  - SS driveshafts Ø0.64 x 894mm
  - Shafts and tendon separated by smaller tubes
  - No distal joint encoders...
5D design – sectioned joints

- Large, local reductions
  - 700:1, reduces driveshaft windup
- Miniature bearings on rigid axes
- Cable transmissions (0.15mm diameter Kevlar)
- Catheter tendon decoupled from rigid joints
  - 0.23 mm, Teflon-coated

58mm = 2.2”

Ø12mm
5D controller design

- Rigid joints as fast as flexible, no frequency partitioning
- Task-space control
  - Control projected tip xyz position, 3DOF < 5DOF
  - Task-space error formed between command and measured tip
    - Joint space control can see divergence between measured and forward IKs
  - Integral + feedforward
Global Search Inverse Kinematics (IK)
- Given $\mathbf{xyz}^*$, find $q_p^*$ that achieves
- 3D task guiding 5D $\rightarrow$ 2D free
- Non-convex: multiple local minima

\[
\begin{align*}
\mathbf{e} &= \left\| \begin{pmatrix} \mathbf{x} \\ \mathbf{y} \\ \mathbf{z} \end{pmatrix}_{\text{tgt}} - \mathbf{FK}(\mathbf{KF}(q^*)) \right\|_2 \\
\mathbf{p} &= \mathbf{q}_{0:4}^* - \mathbf{q}_{0:4}_{\text{last}} \\
\text{cost} &= \mathbf{e} + \mathbf{p}
\end{align*}
\]
5D tracking a real target

- Target moves in a 3D ~circle of Ø90mm
5D tracking a virtual circle

- Moving target replaced with timed, virtual circle

<table>
<thead>
<tr>
<th>Gain</th>
<th>Mean Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.09</td>
<td>5.178°</td>
</tr>
<tr>
<td>0.07</td>
<td>2.360°</td>
</tr>
<tr>
<td>0.06</td>
<td>1.739°</td>
</tr>
</tbody>
</table>
Why the orbiting error?

Contours of current goal (xyz)

- a) IK seeking
- b) joint moves here
- c) actual minimum

kinematic error

last \( q_p \)

Integrated Error

\[ K_i \]

\[ S \]

feedforward

Global Search IK

\[ e = \begin{bmatrix} x \\ y \\ z \end{bmatrix} - \text{FK}(KF) \]

\[ p = |q^*_0 - q_{0,4}^{last}| \]

Tip X [mm]

Gain: Mean Error:

- 0.09 5.178°
- 0.07 2.360°
- 0.06 1.739°

Tip Y [mm]

Tip Z [mm]
Looking forward

Desire increased

**Performance:**
- Increase accuracy, precision, & speed?
  - 4 times faster, same accuracy
  - CL fundamentally limited by first mode
- Reduce or avoid hysteresis?
  - Fine resolution from rigid joint

**Dexterity:**
- Expand the dexterous workspace?
  - Possible given control
- Maintain ‘good’ configurations?
  - Possible given control

Other takeaways:
- Functional design --2-3x clinical scale
- Realized target tracking
- Rigid joints impaired by cable creep → **Rebuild**
- Kinematic errors limit performance → **Implement an online estimator**
- Catheter vibrational mode still limits closed-loop → **Improve open-loop**
  - Forward kinematic improvements are highly valuable
- Plant dynamics change with configuration → **Decouple?**
Thank you

- Questions?