Telemanipulation of Snake-Like Robots for Minimally Invasive Surgery of the Upper Airway

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Surgical Setup in Throat MIS*

endoscope

instrument (tissue shaver)

laryngoscope (cannula for instruments)

*Courtesy of Paul Flint M.D. Johns Hopkins School of Medicine
Limitations of the Surgical Setup

- Long rigid instruments
- Predetermined entry port
- No distal dexterity
- No suturing or functional tissue reconstruction capability
- Motion constraint
- Hand-eye coordination
Human-machine cooperative manipulation in surgery

Situation assessment
Task strategy & decisions
Sensory-motor coordination

- Display
- Sensors
- Online references & decision support
- Manipulation enhancement
- Cooperative control and “macros”

HMCS System

atlases
libraries
Related Works:
Surgical Dexterity Enhancement

• Commercial Systems
  – Zeus
  – Intuitive Surgical Da-Vinci (Endo-Wrist)

• Research Works
  – Dario (3 mm SMA for arthroscopy visualization)
  – Ikuta (15 mm SMA, colonoscopy)
  – Ikuta, Yamamoto, Sasaki (Deep surgical field)
  – Fujie (Dexterity for Brain Surgery)
  – Asai & Mitiishi (5mm snake like device for microsurgery)
  – Salisbury & Intuitive Surgical (Endo-Wrist, 5 mm wire actuated snake)
  – Sastry & Cavusoglu (2-3 DoF ~8mm wrists)
  – Jan Peirs (5 mm wire actuated snake)
  – ….. And many other works
Related Works: Virtual Fixtures

• Virtual fixtures: perceptual overlays designed to enhance performance
  – Active Compliance
    • Rosenberg
    • Stanisic et al.
    • Davies et al.
    • Park et al.
  – Vision Based
    • Marayong et al.
    • Dewan et al.
  – Based on Constrained Control
    • Funda et al.
    • Li et al.
Snake-Like Units (SLU)

- Uses push-pull superelastic backbones & actuation redundancy
- Eliminates dependency on precision joints & backlash
- Simple to manufacture
- Easily downs-scalable to smaller diameters
- Enhanced force application capability

High Level Constrained Control

Steady Hand Robot

Low Level Controller

Current State

Constraint Generation

Registered Model

Optimization Framework

Joint Velocities

K_v

Handle Force
5 Basic Geometric Constraints

(Virtual fixture library)

Optimization Framework

\[ \arg \min_{\Delta \vec{q}} C(\vec{x}(\vec{q} + \Delta \vec{q}), \vec{s}, \vec{x}^d) \]

s. t. \[ A(\vec{x}(\vec{q} + \Delta \vec{q}), \vec{s}) \leq \vec{b}, \]
\[ \vec{s}_{up} \geq s \geq \vec{s}_{low} \geq 0, \]
\[ \Delta \vec{q}_{up} \geq \Delta \vec{q} \geq \Delta \vec{q}_{low} \]

- Stay on a point
- Maintain a direction
- Prevent plane penetrating
- Move along a line
- Rotate around a line

Kapoor, A. Li, M., Taylor, R.H. *Constrained Control for Surgical Assistant Robots*, ICRA 2006
Snake Like Robot
System Architecture

Low Level Controller → High Level Controller
x2 (Left & Right)

High Level Controller → Low Level Controller
x2 (Left & Right)
Master Side Low-Level Controller

- The low-level is a PD Joint Controller
- The force applied by user is treated as disturbance
- Under quasi-static approximation, position error is proportional to user force
A constrained least squares problem is solved for joint velocities.
Objective function determines the desired outcome.
Constraints modify the behavior of the robot to a given input.
Master Side High-Level Controller

\[
\begin{align*}
\min_{\Delta \bar{q}_m} & \left\| W_{m,t} \left( \Delta x_m - K_a \left[ p^e_m ; \theta_m \omega_m \right] \right) \right\| \\
& + \left\| W_{m,s} \left( \Delta x_m - K_f \left[ p^e_{m,s} ; \theta_{m,s} \omega_{m,s} \right] \right) \right\| \\
& + \left\| W_{m,j} \Delta q_m \right\|
\end{align*}
\]

- **Objectives:**
  - Minimize error between desired motion and actual motion
  - Oppose motion that increases master-slave tracking error
  - Minimize the extraneous motion of the joints, and
  - Avoid large incremental joint motions that could occur near singularities
Master Side High-Level Controller

\[
\min_{\Delta \theta_m} \left\| W_{m,t} \left( \Delta x_m - K_a \left[ p^e_m; \theta_m \omega_m \right] \right) \right\| \\
+ \left\| W_{m,s} \left( \Delta x_m - K_f \left[ p^e_{m,s}; \theta_{m,s} \omega_{m,s} \right] \right) \right\| \\
+ \left\| W_{m,j} \Delta q_m \right\|
\]

- Objectives:
  - Minimize error between desired motion and actual motion
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Master Side High-Level Controller

\[
\min_{\Delta \hat{q}_m} \left\| W_{m,t} (\Delta x_m - K_a [p^c_m; \theta_m \omega_m]) \right\| \\
+ \left\| W_{m,s} (\Delta x_m - K_f [p^c_{m,s}; \theta_{m,s} \omega_{m,s}]) \right\| \\
+ \left\| W_{m,j} \Delta q_m \right\|
\]

- **Objectives:**
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Master Side High-Level Controller

- **Constraints:**
  - General form: $H_{m,j} \cdot \Delta q_m \geq h_{m,j}$
  - Not allow motion outside joint range
  - Not allow motion that exceeds joint velocity limits
  - Additional constraints can be added from the VF Library

\[ \begin{bmatrix} I \\ -I \\ I \\ -I \end{bmatrix} \Delta q_m \geq \begin{bmatrix} \frac{q_mL - q_m}{m} \\ q_m - q_m, U \\ \dot{q}_m, U \cdot \Delta t \\ \dot{q}_m, U \cdot \Delta t \end{bmatrix} \]
Slave Side Low-Level Controller

- The low-level is a PID Joint Controller
- The two DOF of each snake are parameterized by two angles
  - The bending angle of primary backbone
  - The orientation of bending plane with respect to base XZ plane
Slave Side High-Level Controller

**Objectives:**
- Minimize error between desired motion and actual motion
- Minimize the extraneous motion of the joints, and
- Avoid large incremental joint motions that could occur near singularities

\[
\min_{\Delta q_s} \left\| W_{s,t} \left( \Delta x_s - K_a \left( p_s^e; \theta_s \omega_s \right) \right) \right\|
\]
\[
+ \left\| W_{s,j} \Delta q_s \right\|
\]

such that
\[
\begin{bmatrix}
I & -I \\
-I & I \\
\end{bmatrix} \Delta q_s \geq \begin{bmatrix}
q_s, L - q_s \\
q_s - q_s, U \\
\dot{q}_s, U \cdot \Delta t \\
\dot{\dot{q}}, U \cdot \Delta t \\
\end{bmatrix}
\]

**Constraints:**
- Not allow motion outside joint range
- Not allow motion that exceeds joint velocity limits
- More constraints can be added from the VF Library
Experimental Setup
Master

![Experimental Setup Image]
Experimental Setup

Slave
Experimental Setup
Roll motion

Roll Motion about the Gripper
Without Lateral Motion of Base Joints
Experimental Setup

S-bend motion
Experimental Setup
Surgeon’s view
Experimental Setup
Fish Hook

Pass a Needle through the Fish Hook Eyelet
Surgeon's View via HMD Display
Conclusion

• A novel system designed considering special requirements for MIS of throat
• High-level control of a telesurgical system
• Efficient use of dexterity avoids motion of proximal joints
• Validation experiments using suturing phantom
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