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

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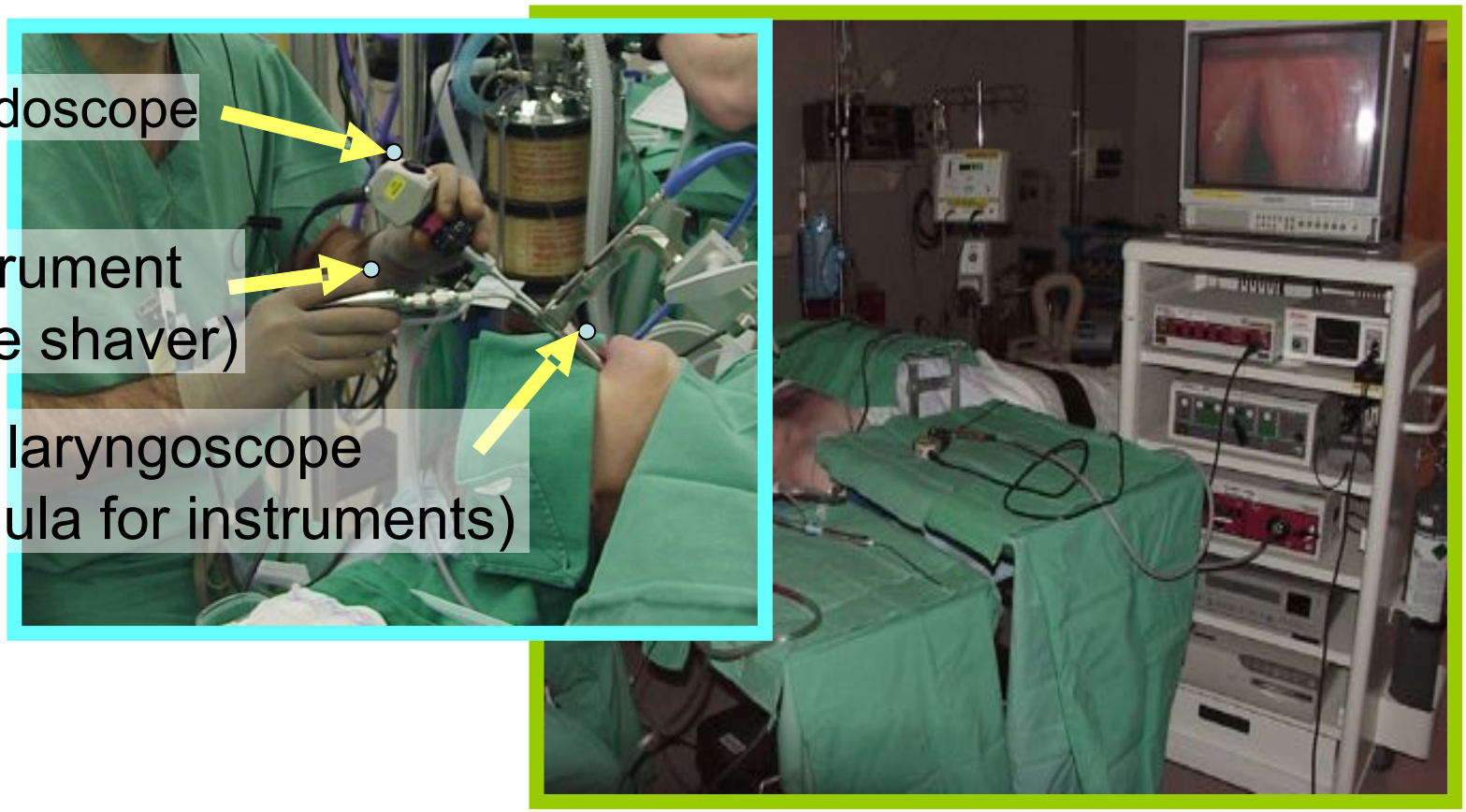
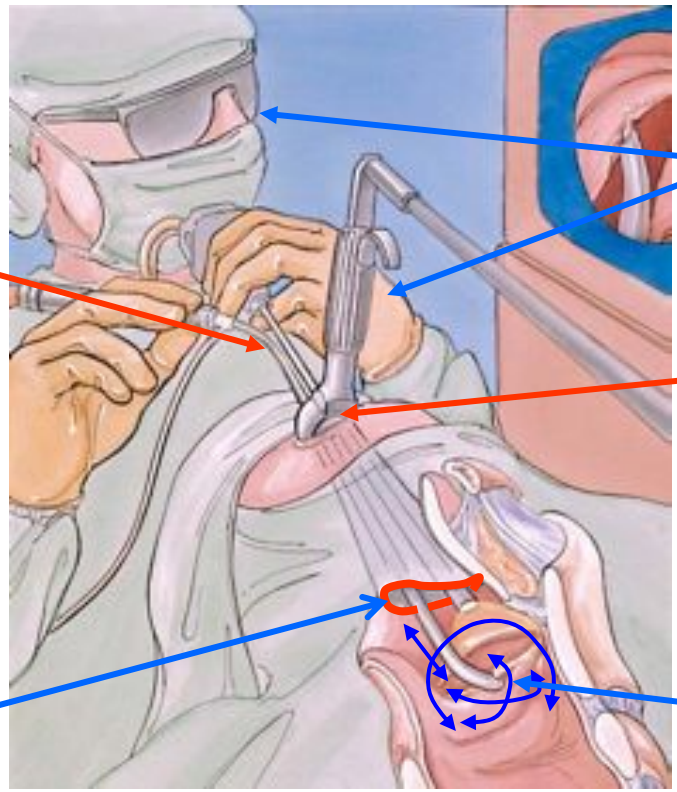
Surgical Setup in Throat MIS*



*Courtesy of Paul Flint M.D. Johns Hopkins School of Medicine

Limitations of the Surgical Setup



Hand-eye coordination

Long rigid instruments

Predetermined entry port

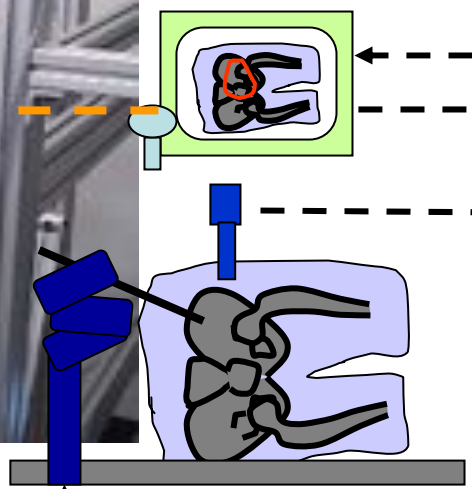
motion constraint

No distal dexterity

No suturing or functional tissue reconstruction capability

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”

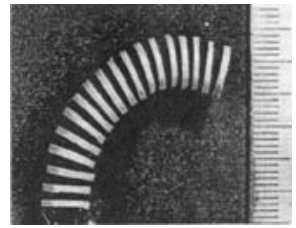
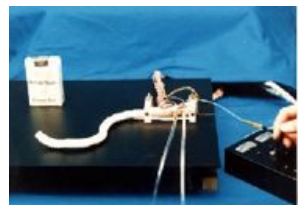
atlases

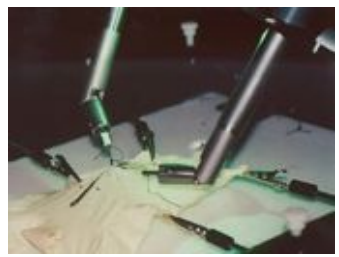
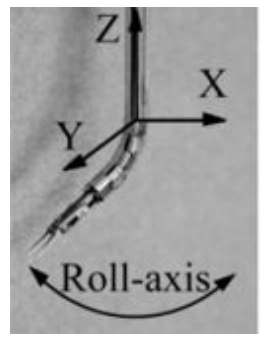
libraries

HMCS System

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 & Mituishi (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**

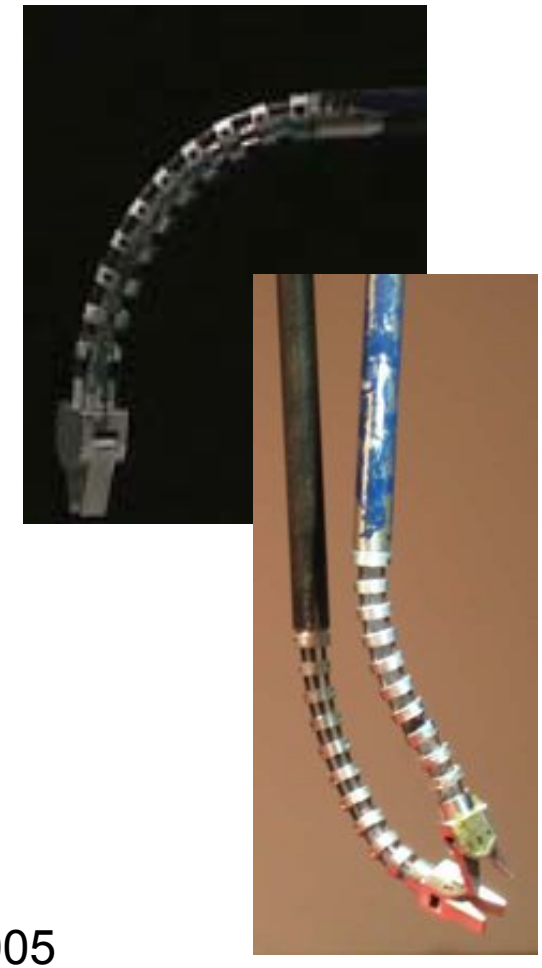



Related Works: Virtual Fixtures

- 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



Simaan N. *et al,* MICCAI 2004, ICRA 2004, ICRA 2005

High Level Constrained Control

Steady Hand Robot

Low Level Controller

Handle Force

K_v

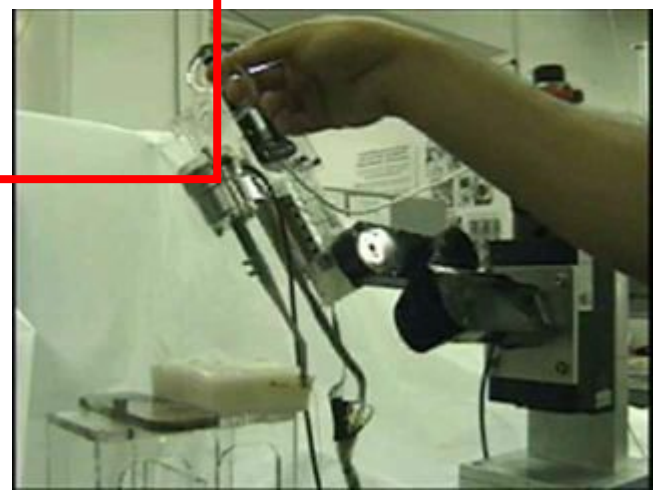
Optimization Framework

Joint Velocities

Current State

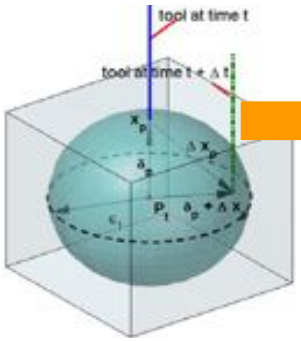
Constraint Generation

Registered Model



5 Basic Geometric Constraints

(Virtual fixture library)



Stay on a point

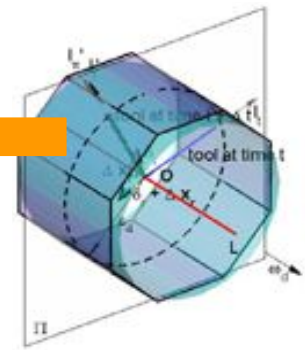
Optimization Framework

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

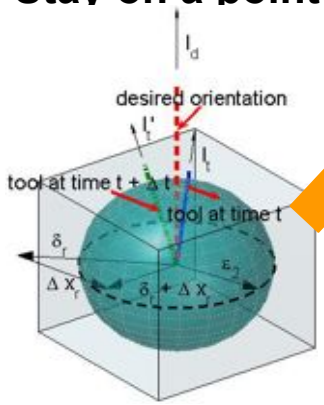
$$\text{s.t.} \quad A(\vec{x}(\vec{q}+\Delta\vec{q}),\vec{s}) \le \vec{b},$$

$$\vec{s}_{up} \ge s \ge \vec{s}_{low} \ge 0,$$

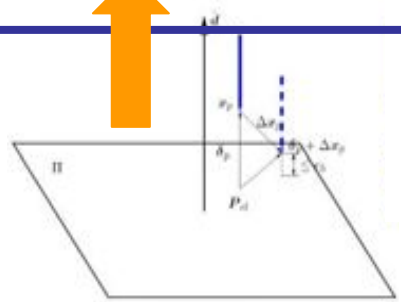
$$\Delta\vec{q}_{up} \ge \Delta\vec{q} \ge \Delta\vec{q}_{low}$$



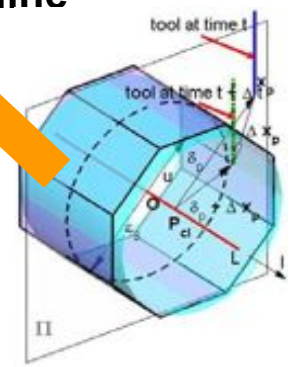
Move along a line



Maintain a direction



Prevent plane penetrating



Rotate around a line

Kapoor, A. Li, M., Taylor, R.H. *Constrained Control for Surgical Assistant Robots,* ICRA 2006

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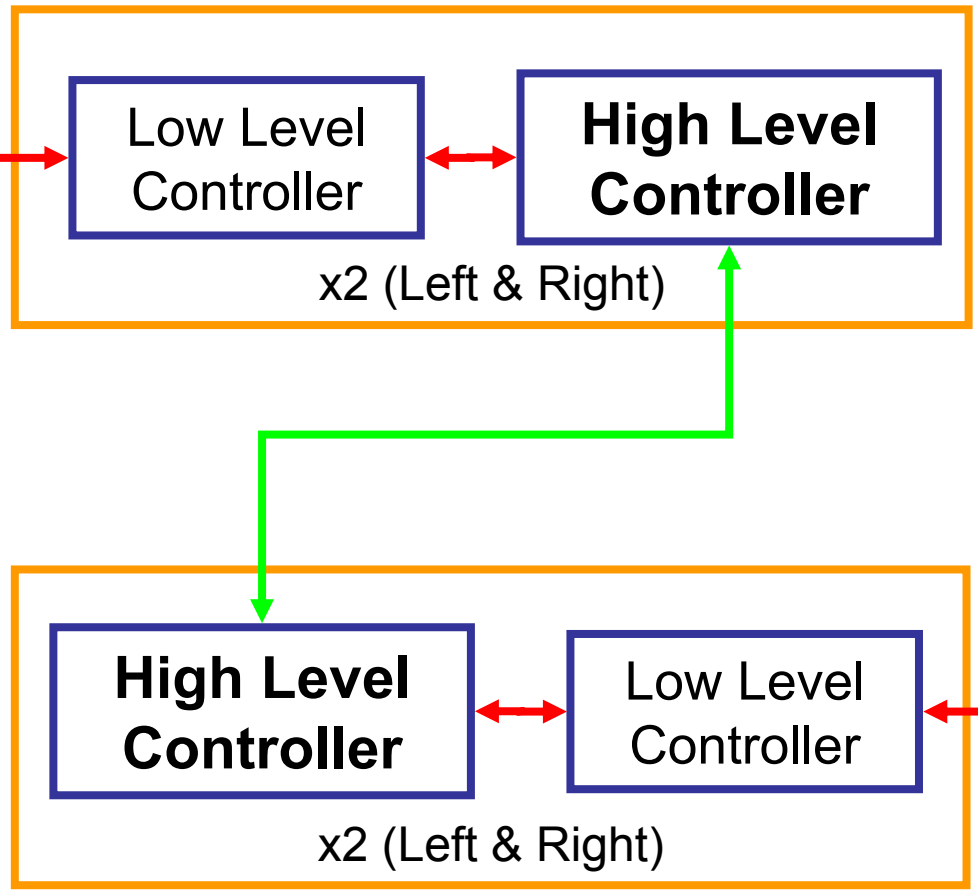
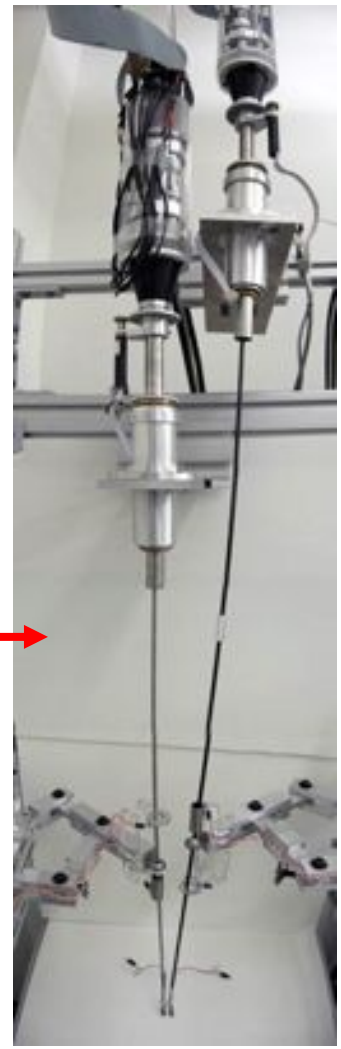
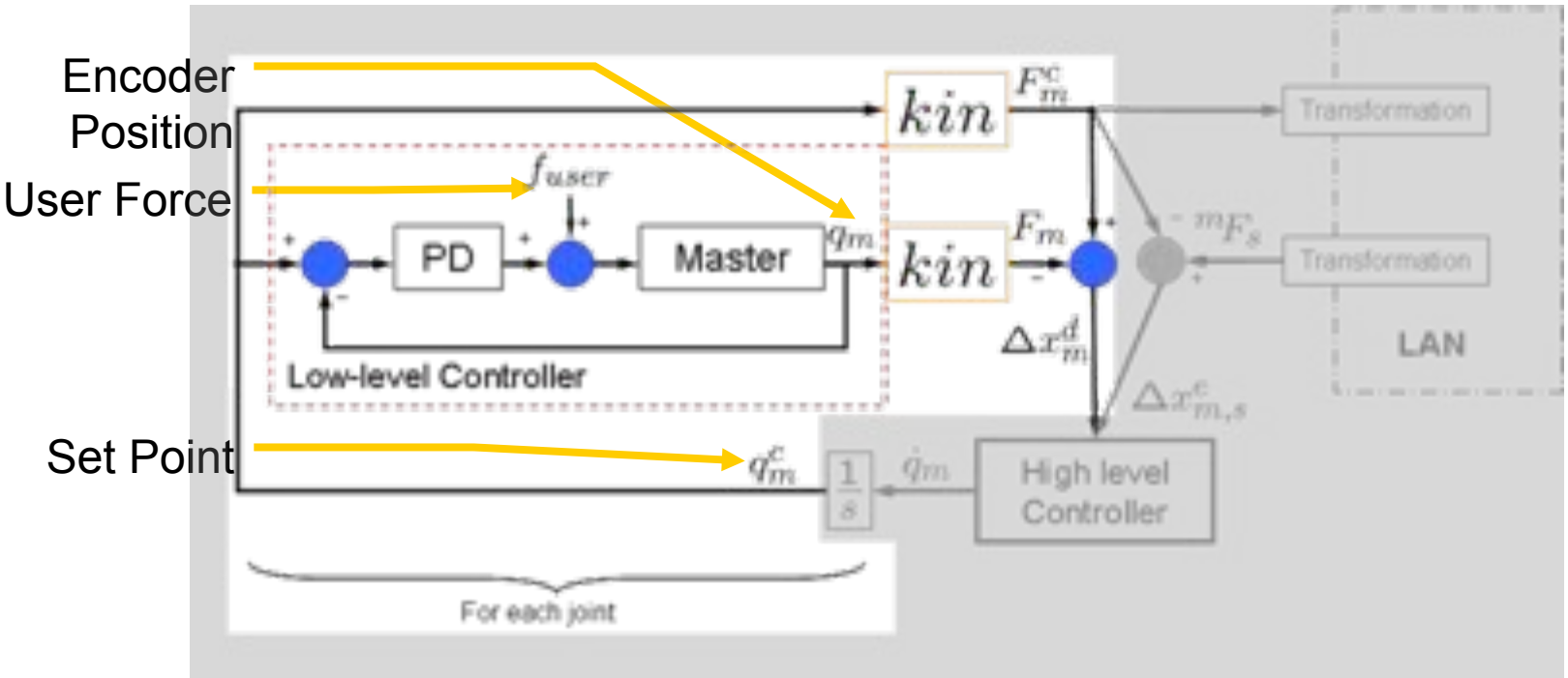
Snake Like Robot

System Architecture



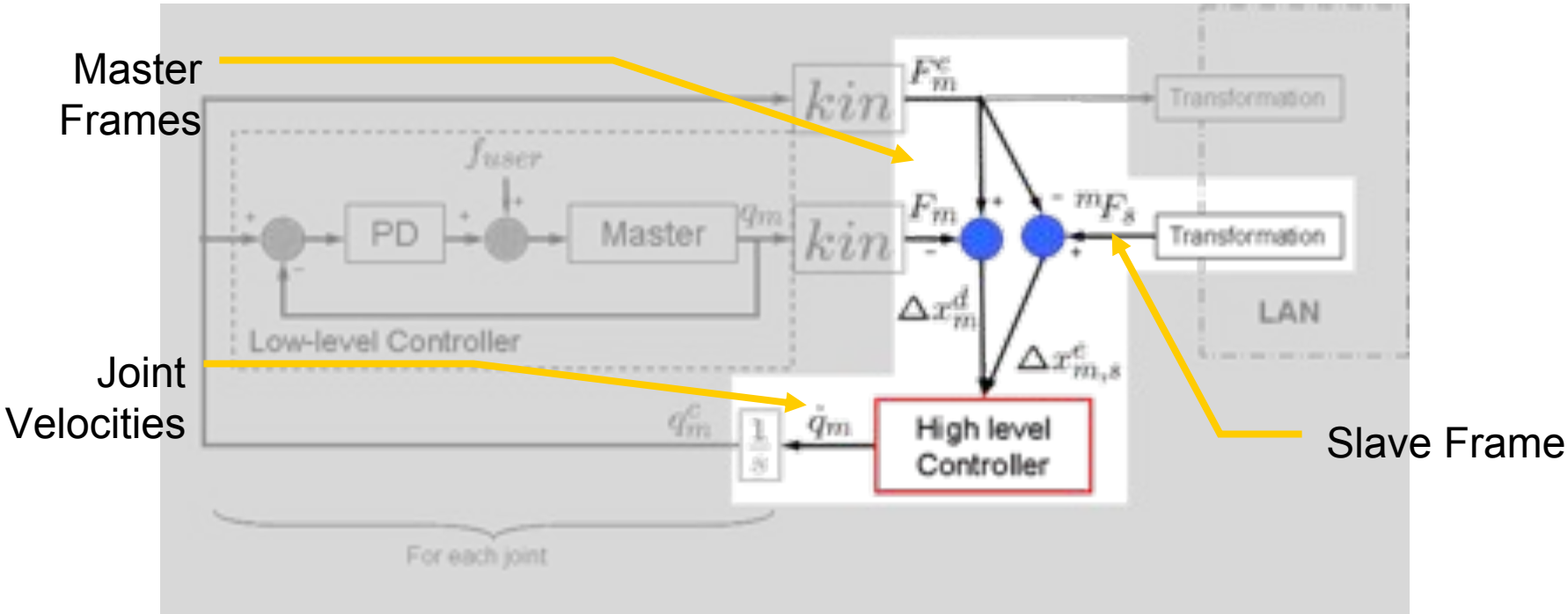


Master Side Low-Level Controller



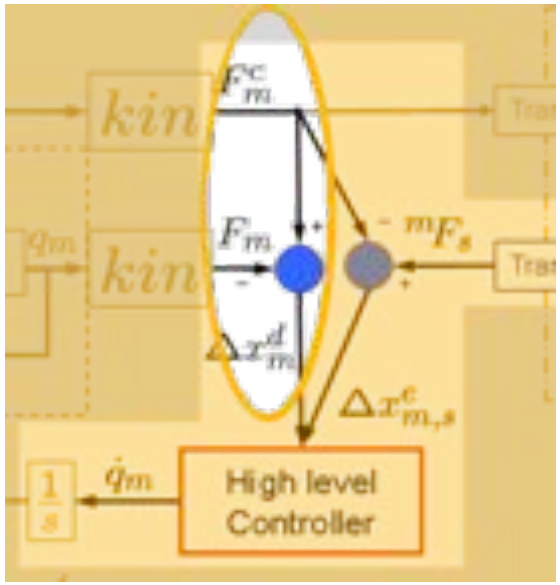
- The low-level is a PD Joint Controller
- The force applied by user is treated as disturbance
- Under quasi-static approximation, position error is proportional to user force

Master Side High-Level Controller



- 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



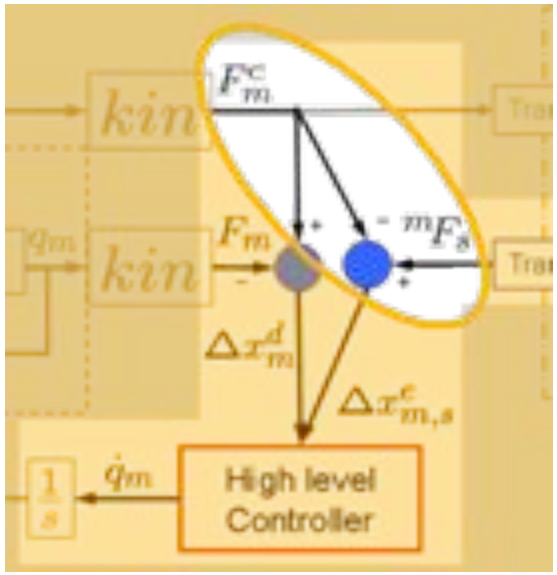
$$\min_{\Delta\vec{q}_m} \left\| W_{m,t} \left(\Delta x_m - K_a \left[p_m^e ; \theta_m \omega_m \right] \right) \right\|$$

$$+ \left\| W_{m,s} \left(\Delta x_m - K_f \left[p_{m,s}^e ; \theta_{m,s} \omega_{m,s} \right] \right) \right\|$$

$$+ \left\| W_{m,j} \Delta q_m \right\|$$

- **Objectives**:
  - Minimize error between desired motion and actual motion
  - 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



$$\min_{\Delta\vec{q}_m} \left\| W_{m,t} \left(\Delta x_m - K_a \left[p_m^e ; \theta_m \omega_m \right] \right) \right\|$$

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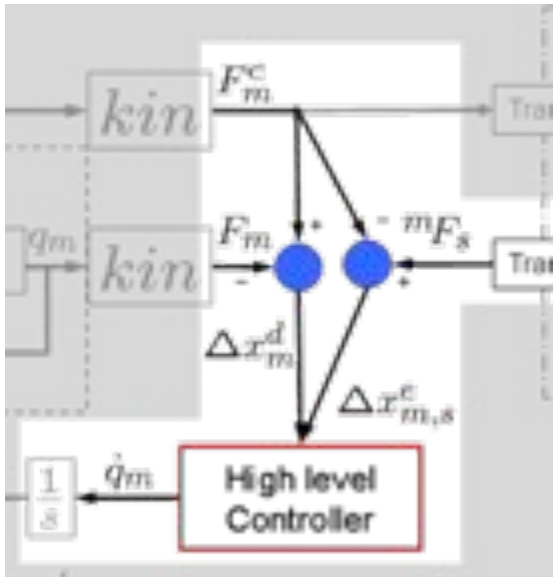

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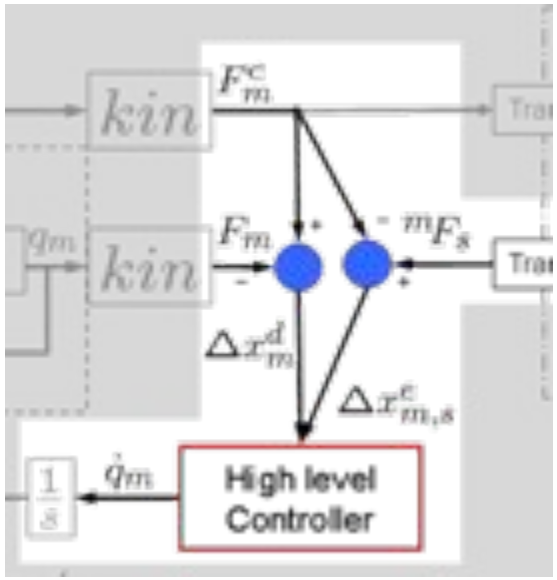
Master Side High-Level Controller

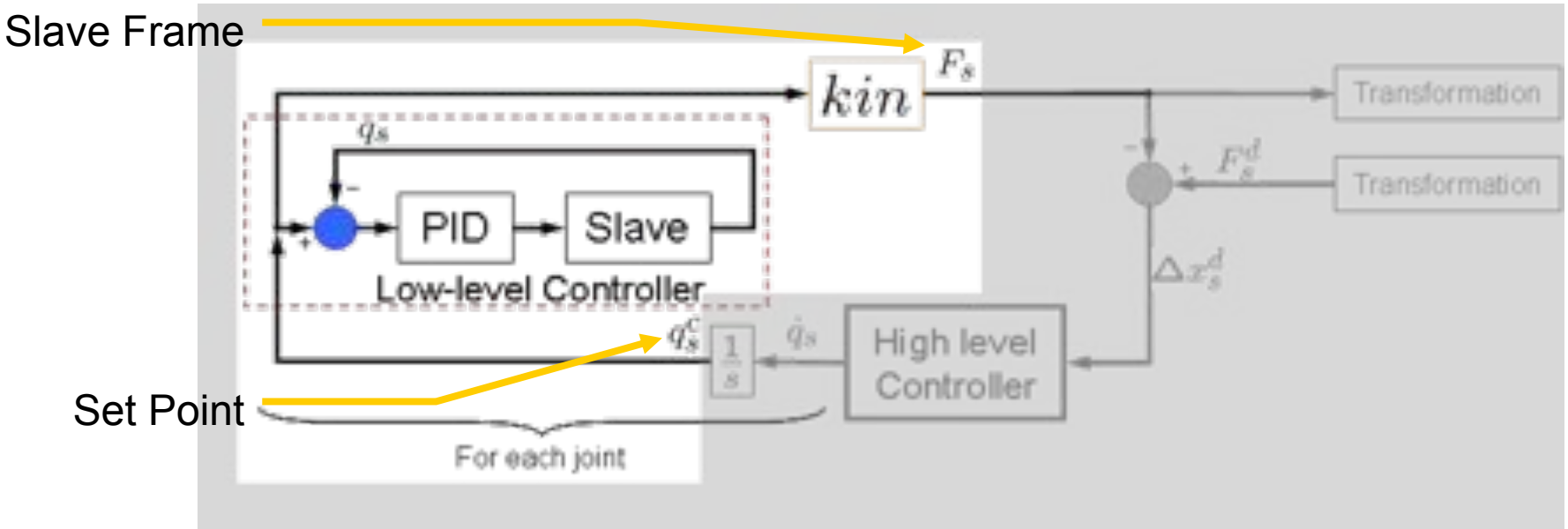


$$H_m \Delta q_m \geq h_m$$

$$\text{that is} \begin{bmatrix} I \\ -I \\ I \\ -I \end{bmatrix} \Delta q_m \geq \begin{bmatrix} q_{m,L} - q_m \\ q_m - q_{m,U} \\ \dot{q}_{m,U} \cdot \Delta t \\ \dot{q}_{m,U} \cdot \Delta t \end{bmatrix}$$

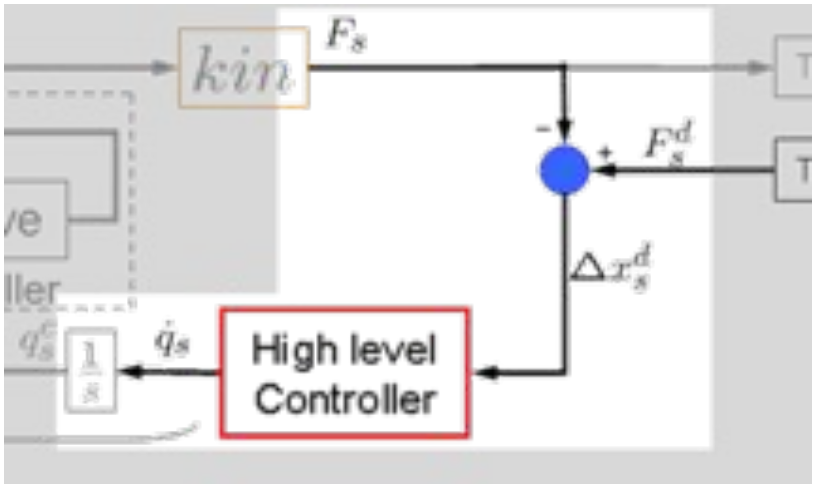
- **Constraints**:
  - General form: $H_{m,j} \cdot \Delta q_m \geq h_{m,j}$
  - Not allow motion outside joint range
  - Not allow motion that exceeds joint velocity limits
  - Additional constraints can be added from the VF Library

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



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

$$\text{such that} \begin{bmatrix} I \\ -I \\ I \\ -I \end{bmatrix} \Delta q_s \geq \begin{bmatrix} q_{s,L} - q_s \\ q_s - q_{s,U} \\ \dot{q}_{s,U} \cdot \Delta t \\ \dot{q}_{s,U} \cdot \Delta t \end{bmatrix}$$

- **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
- **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

Slave

Experimental Setup

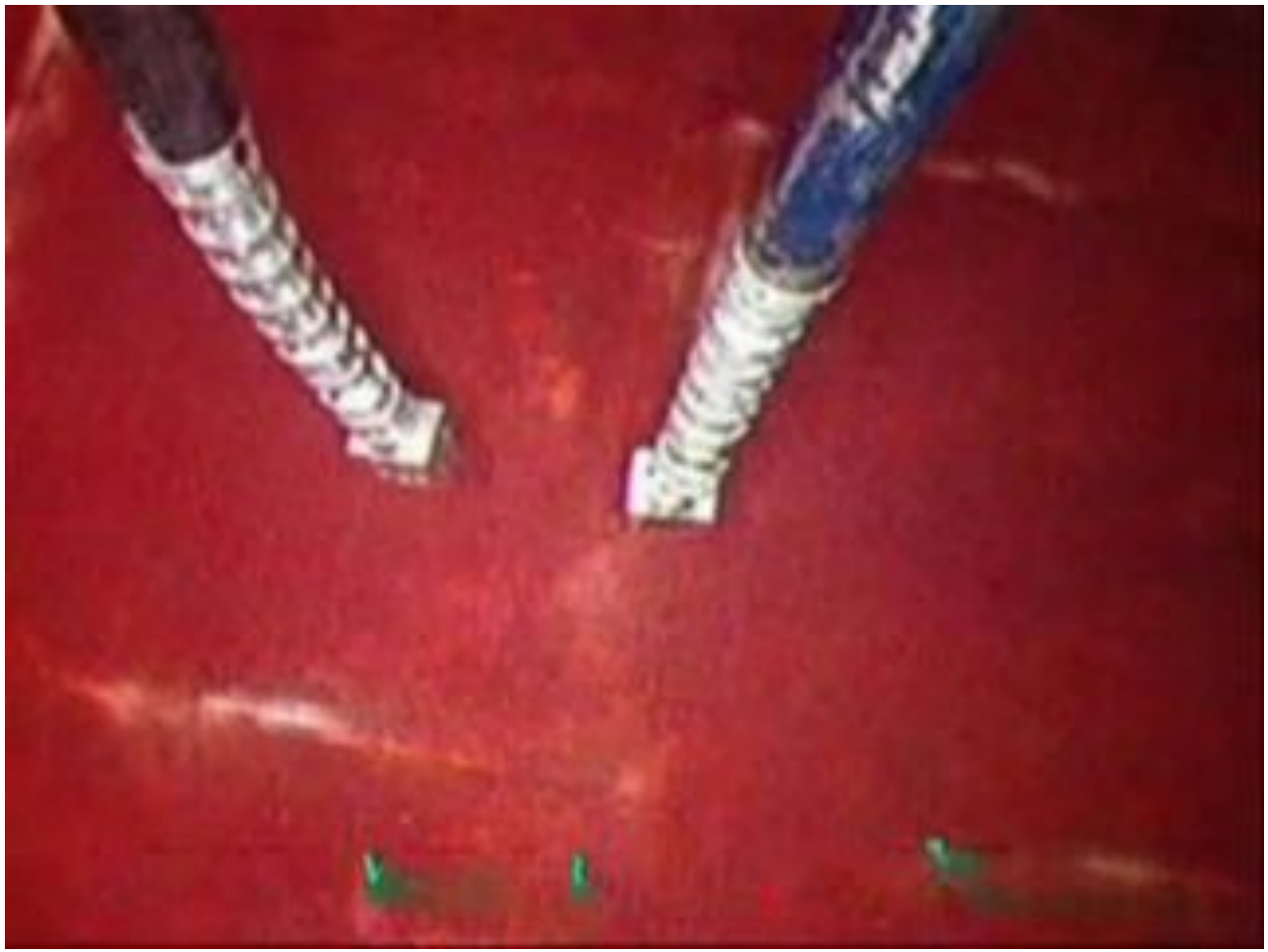
Roll motion

Experimental Setup

S-bend motion

Experimental Setup

Surgeon's view



Experimental Setup

Fish Hook

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

Acknowledgements

- Dr. Paul Flint, School of Medicine, Johns Hopkins University.
- NSF Research Grant #EEC9731478 and #IIS9801684
- NIH #R21 – B004457-01
- Johns Hopkins and Columbia University Internal Funds