Suturing in Confined Spaces: Constrained Motion Control of a Hybrid 8-DoF Robot

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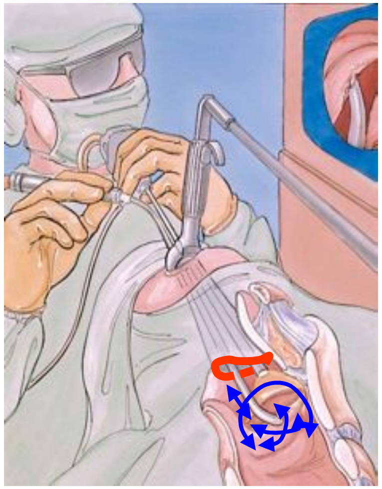
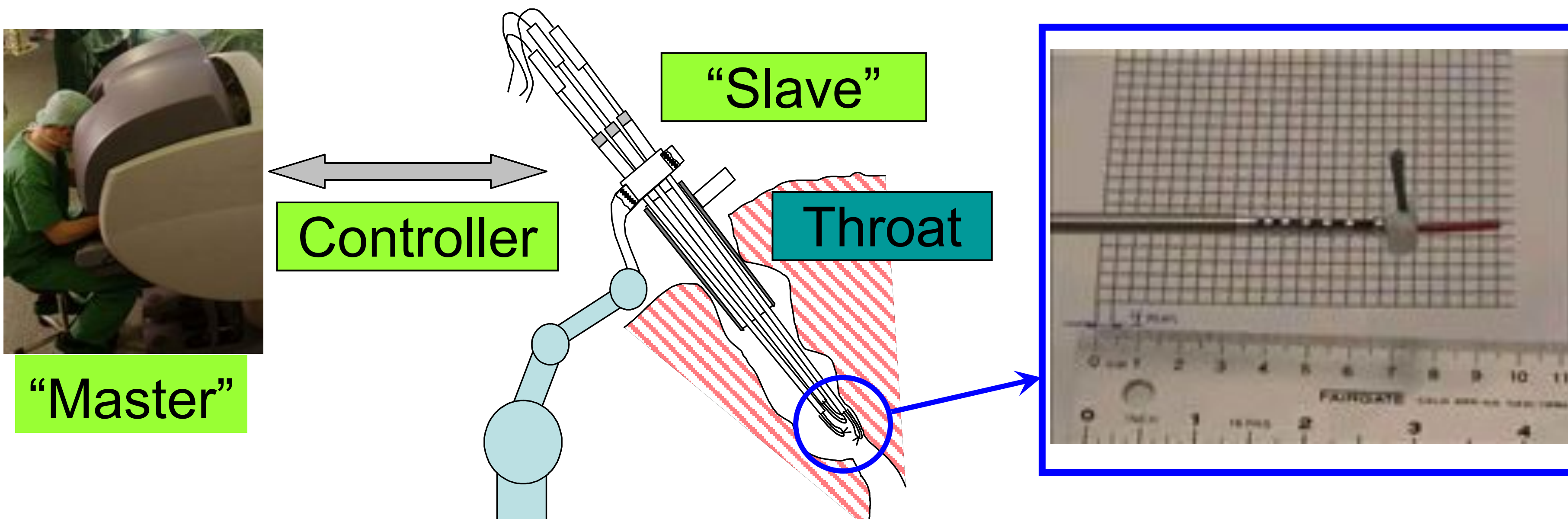
Control for Robot-assisted MIS of the Throat



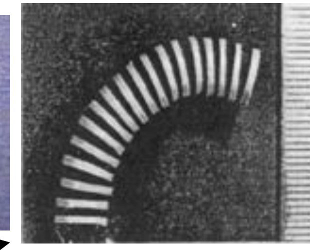
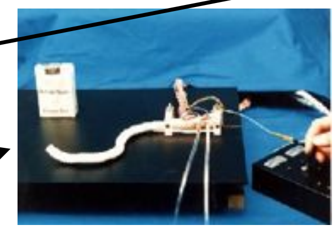
<u>This paper is about</u>

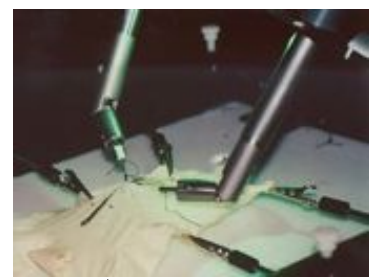
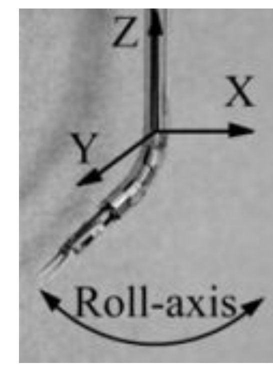
- *Kinematic modeling 8 DoF hybrid robot*
- *High level real-time control algorithm for suturing*
- Experimental validation

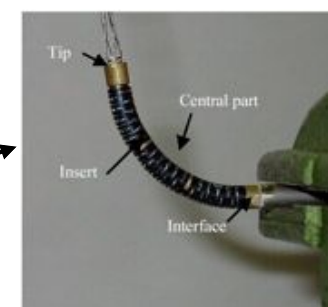


Previous Works: Surgical Dexterity Enhancement

- **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**

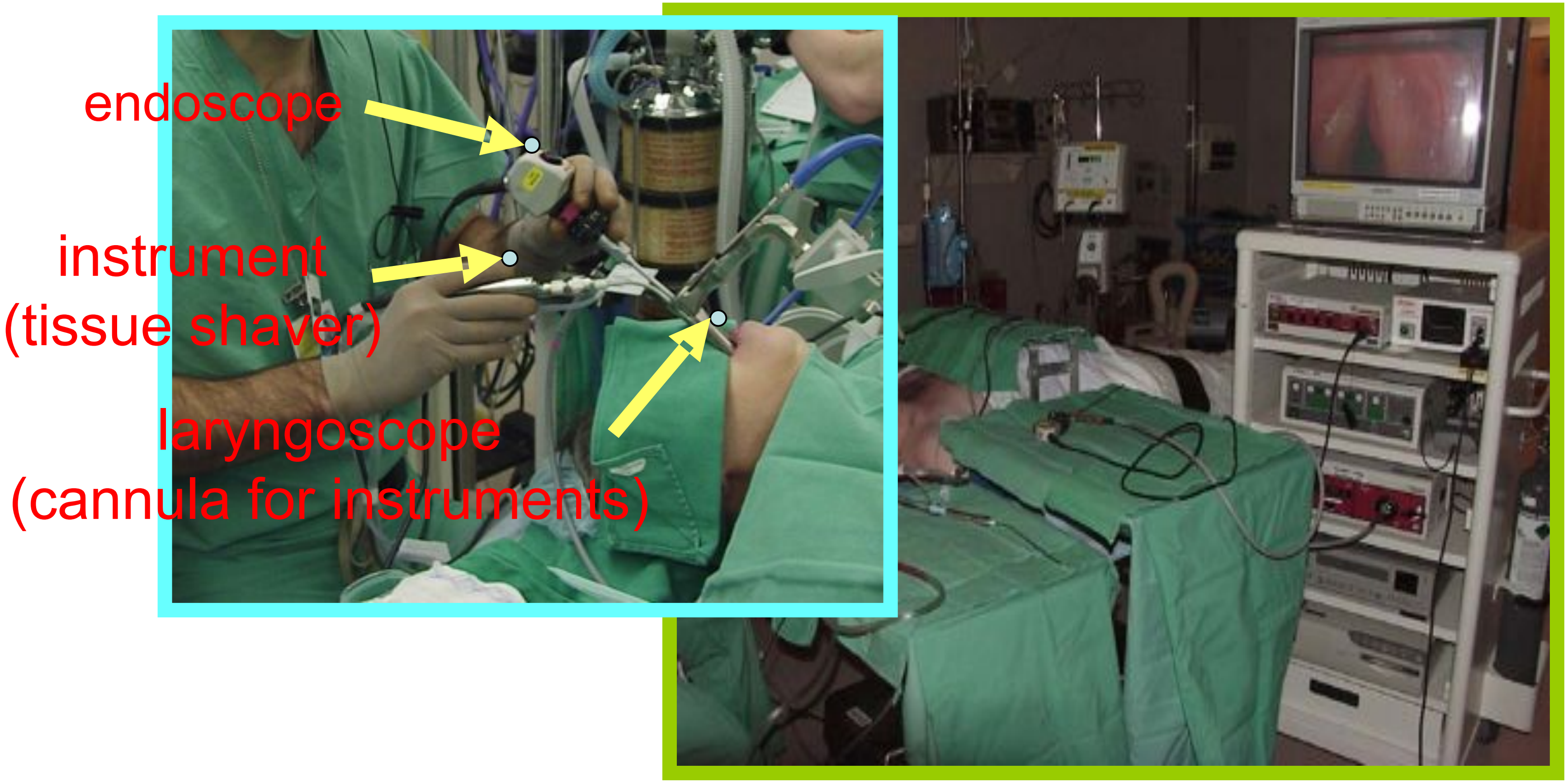





Previous Work: Control

- Redundancy resolution [**Yoshikawa**, **Nakamura** et al, **Hirose**, **Klein** et al.]
- Hyper-redundant robots [**Chirikjian** et al, **Angeles & Zanganeh**]
- Constrained control [**Funda** et al]

Surgical Setup in Throat MIS*



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

Limitations of the Surgical Setup

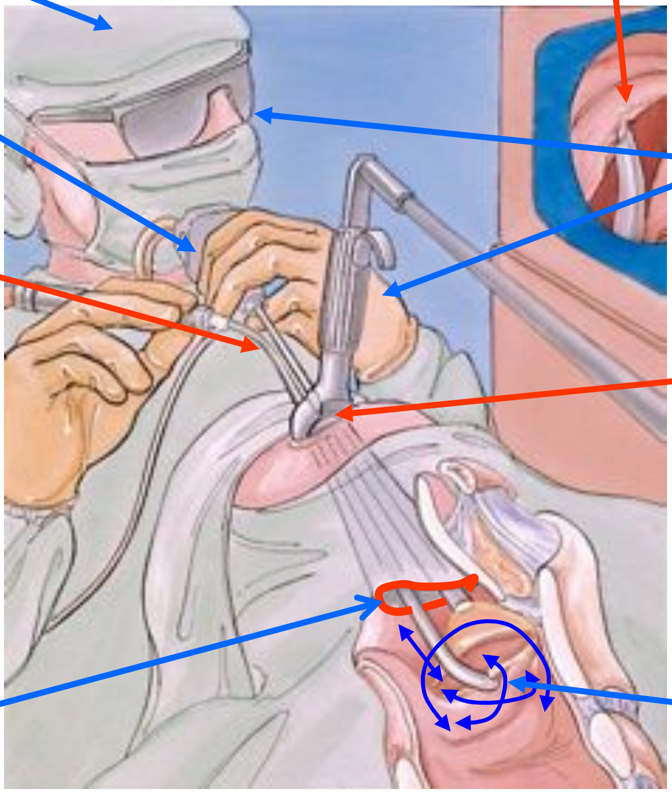
Haptic information deficiency

View limited by soft tissue

Multiple tools

Hand-eye coordination

Long rigid instruments



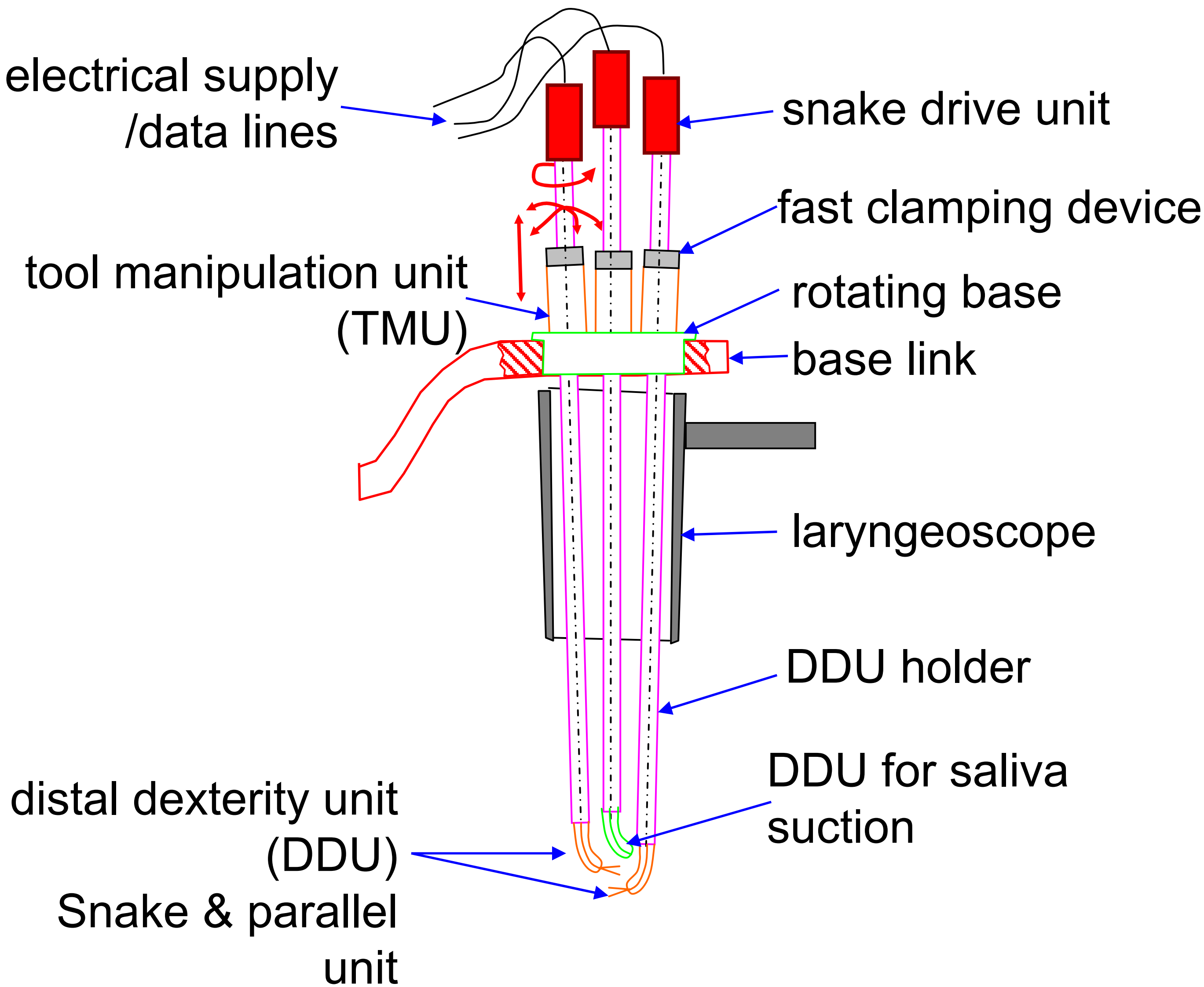
Predetermined entry port

4 DoF motion constraint

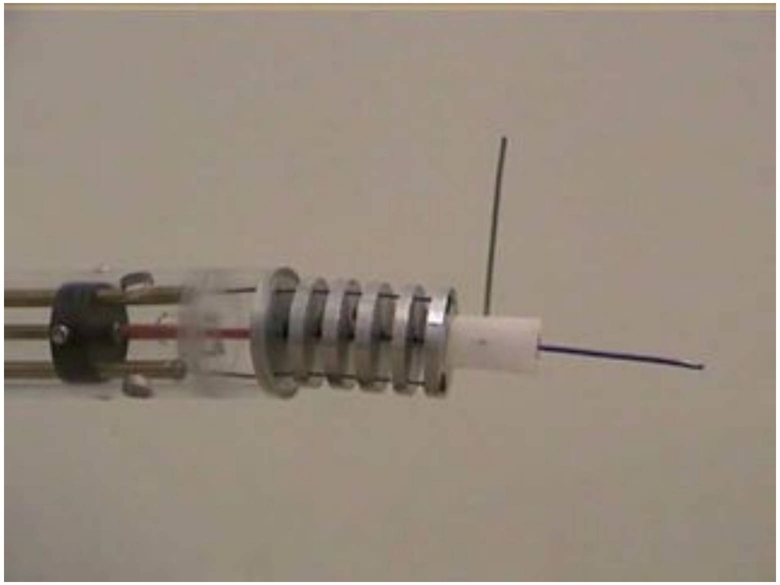
No distal dexterity

No suturing or functional tissue reconstruction capability

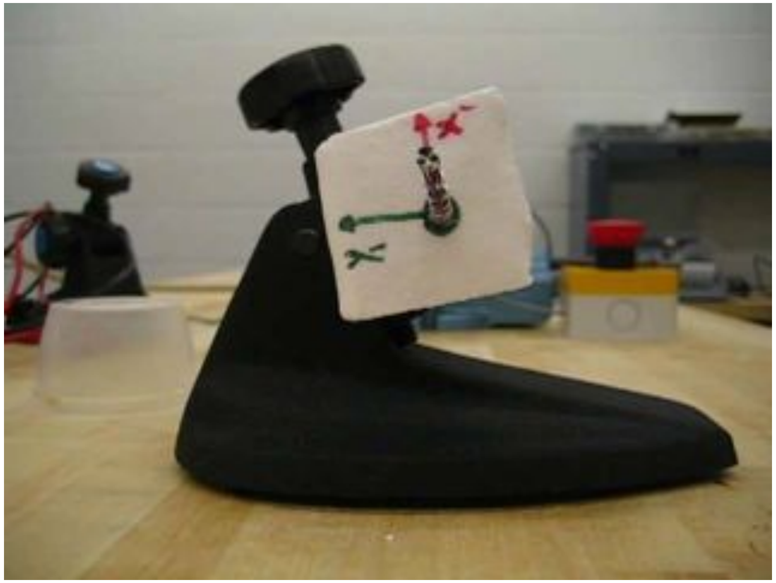
Dexterous Slave for Confined Spaces



The Snake-Like Units (SLU)



27.6mm “Large Snake”

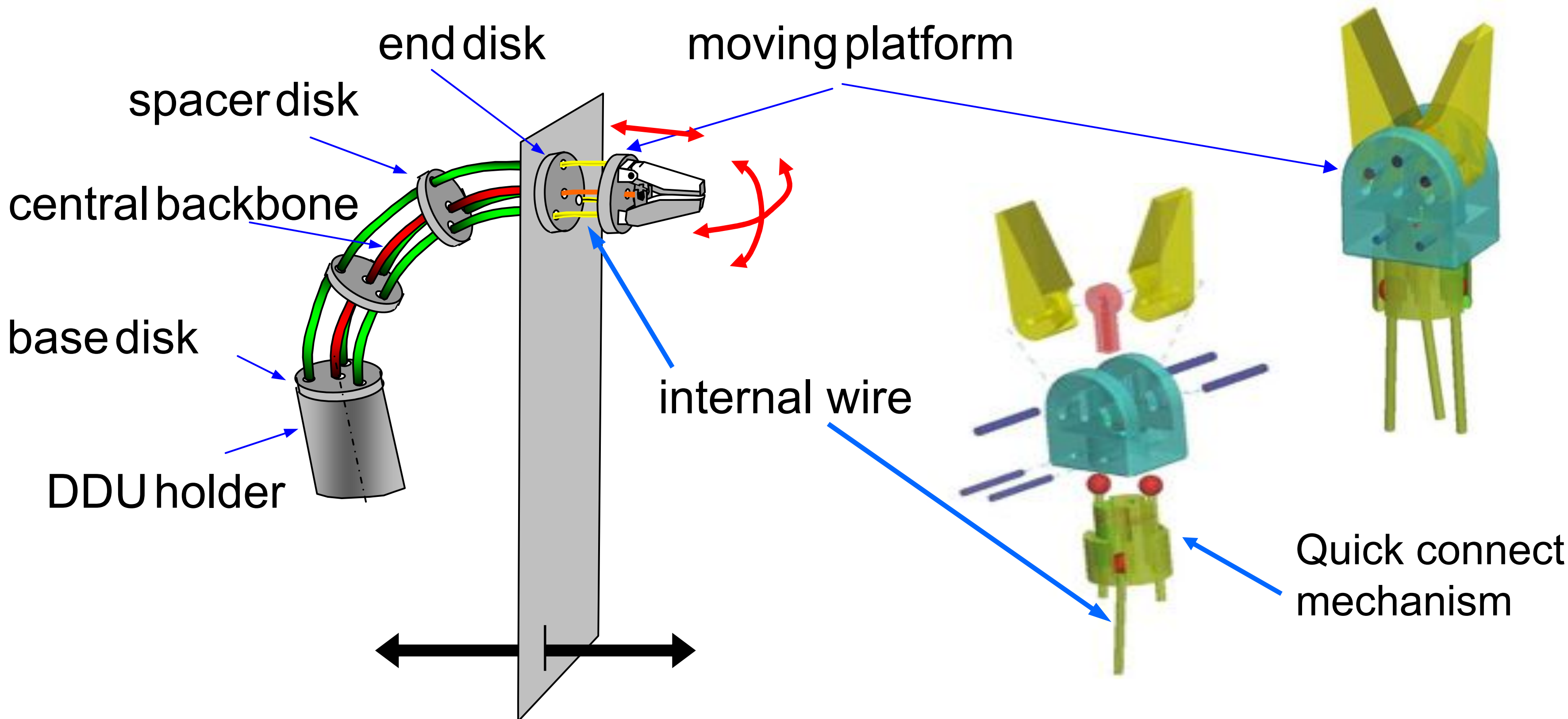


4mm “Small Snake”

Previous works:

Walker & Gravange: snakes using a single flexible backbone & wire actuation

The Distal Dexterity Unit (DDU)



Snake-like unit

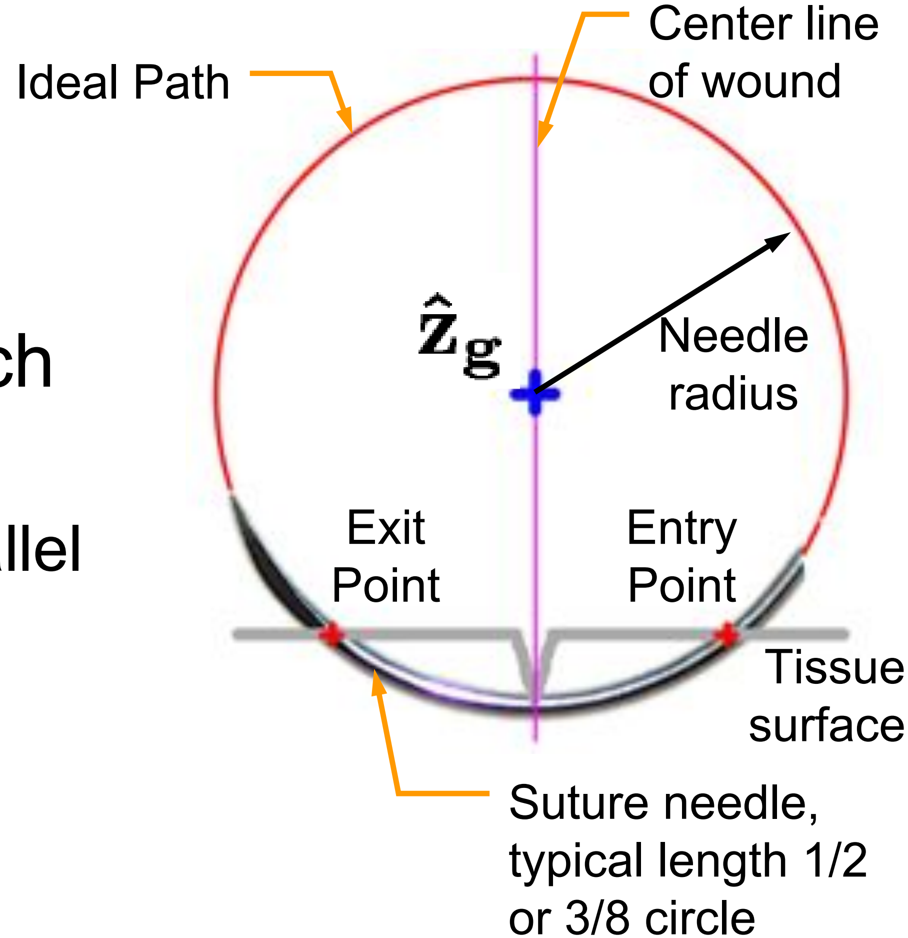
Parallel Manipulation Unit

Can be used for: suturing, suction, light, visualization, drug delivery…..

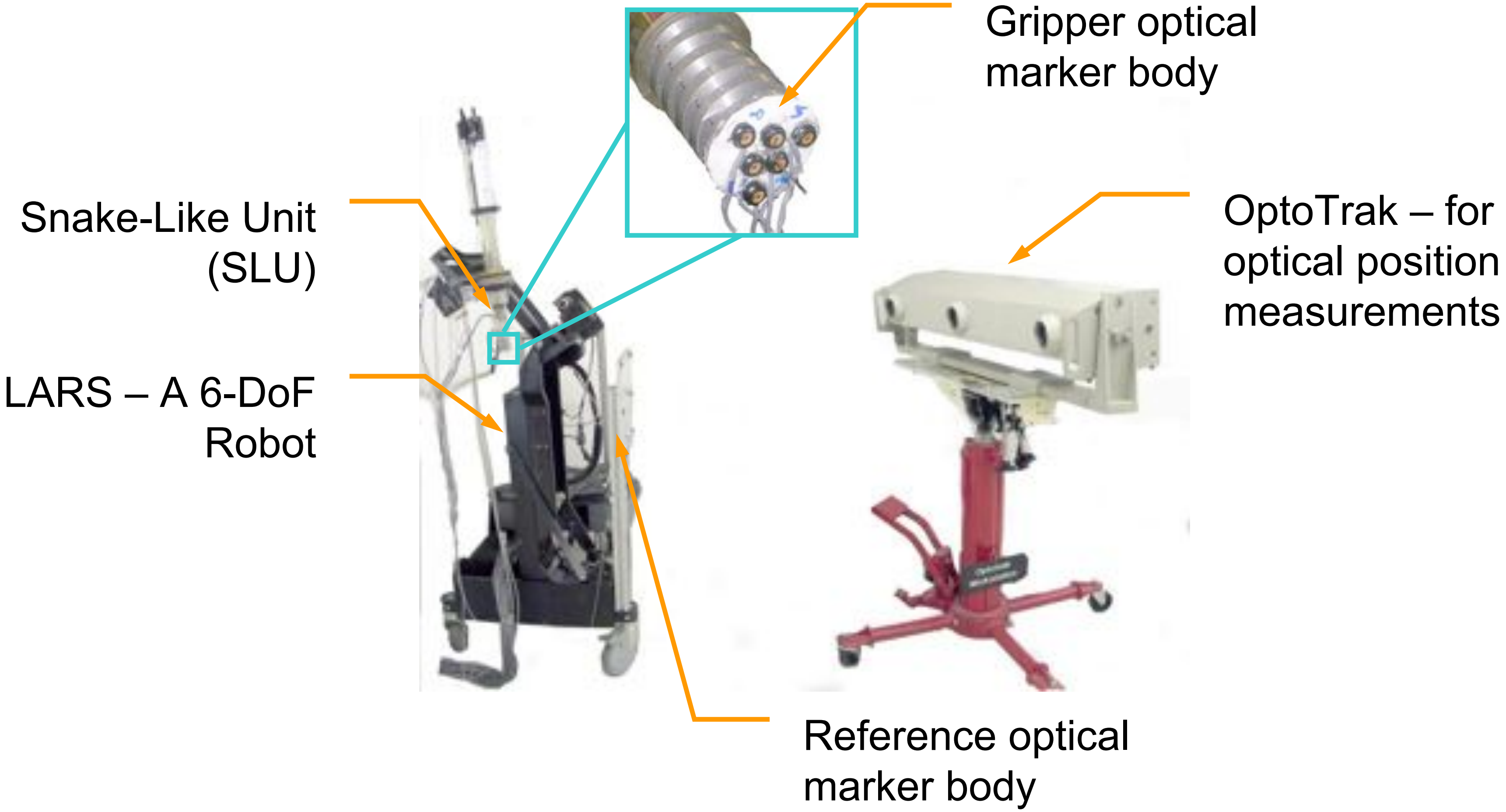
Simple and cheap to fabricate. No backlash. Actuation redundancy.

Problem Statement: Task Model for Suturing

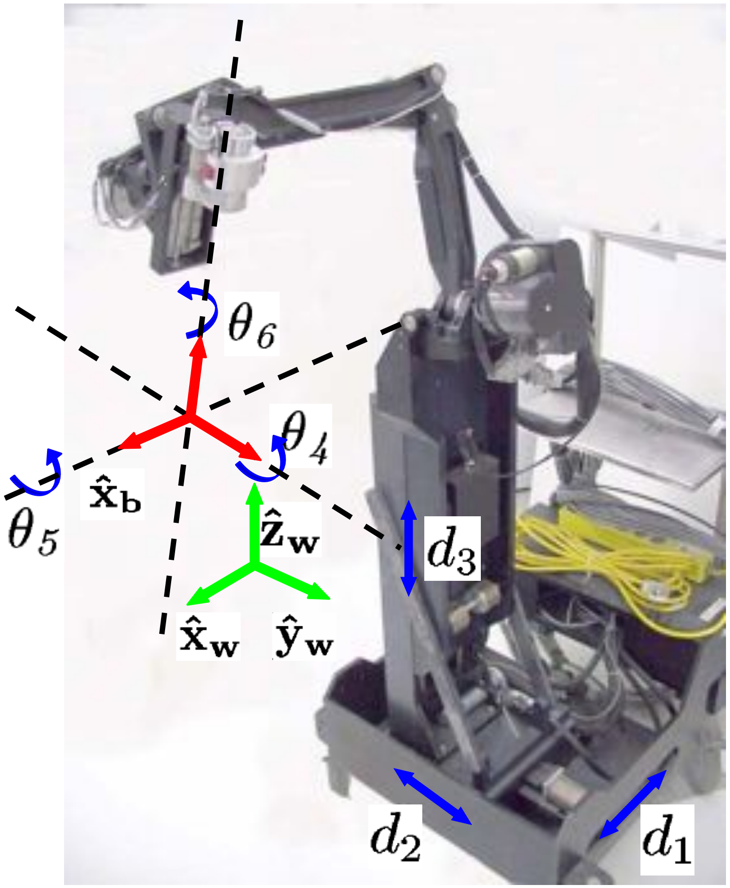
- Suture needle is circular with known radius
- Attached to SLU such that
  - Needle plane is parallel
  - Center of the needle lies along $\hat{\mathbf{z}}_{\mathbf{g}}$
- Ideal path



Our experimental setup



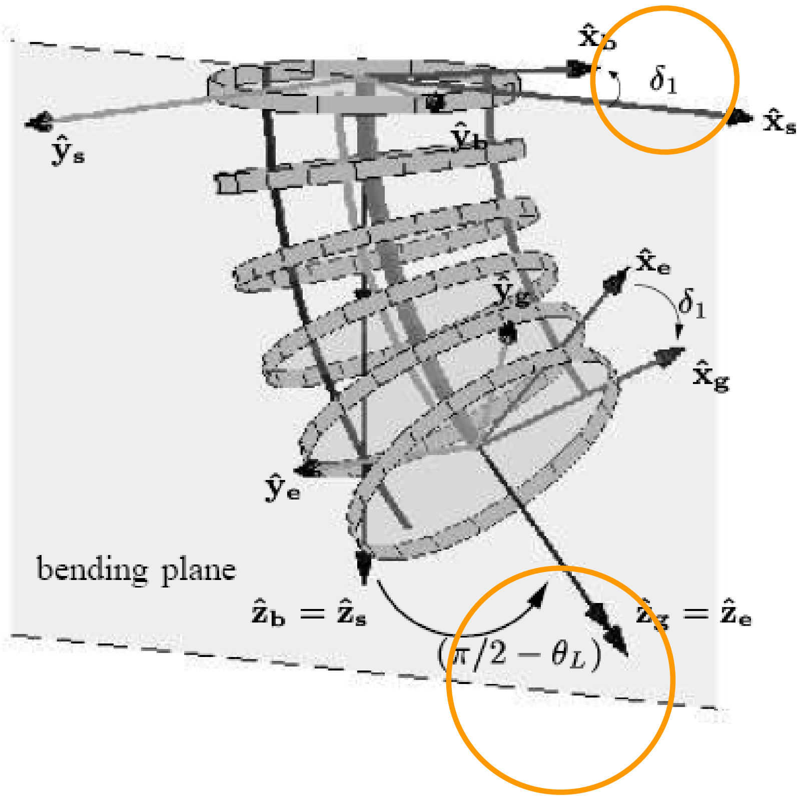
Kinematics of LARS



$$
\begin{aligned}
{}^{w}\mathbf{T}_b = & \left[\mathbf{I}|d_1\hat{\mathbf{x}}_\mathbf{w}\right]\left[\mathbf{I}|d_2\hat{\mathbf{y}}_\mathbf{w}\right]\left[\mathbf{I}|d_3\hat{\mathbf{z}}_\mathbf{w}\right] \\
& \times \left[\mathbf{R}\left(\hat{\mathbf{y}}_\mathbf{w},\theta_4\right)|\mathbf{0}\right]\left[\mathbf{R}\left(\hat{\mathbf{x}}_\mathbf{w},\theta_5\right)|\mathbf{0}\right] \\
& \times \left[\mathbf{I}|\mathbf{p}_{offset}\right]\left[\mathbf{R}\left(\hat{\mathbf{x}}_\mathbf{w},\pi\right)|\mathbf{0}\right]\left[\mathbf{R}\left(\hat{\mathbf{z}}_\mathbf{w},\theta_6\right)|\mathbf{0}\right]
\end{aligned}
$$

- A 6-DoF serial chain
- Has a “remote center of motion”
- Kinematics similar to proposed design

Kinematics of DDU



$$\mathbf{p}_{gb}^{b} = \mathbf{R}\left(\hat{\mathbf{z}}_{\mathbf{b}}, -\delta\right) \mathbf{p}_{gb}^{s}$$

$${}^{b}\mathbf{R}_{g} = \mathbf{R}\left(\hat{\mathbf{z}}_{\mathbf{b}}, -\delta\right) \mathbf{R}\left(\hat{\mathbf{y}}_{\mathbf{s}}, \pi/2 - \theta_{L}\right) \mathbf{R}\left(\hat{\mathbf{z}}_{\mathbf{e}}, \delta\right)$$

where

$$\mathbf{p}_{gb}^{s} = \left[\int_0^L \cos(\theta(s))ds, \quad 0, \quad \int_0^L \sin(\theta(s))ds \right]^t$$

We assume a constant bending model, i.e

$$\theta(s) = \pi/2 + as; \text{ where}, a = \left(\theta_L - \pi/2\right)/L$$

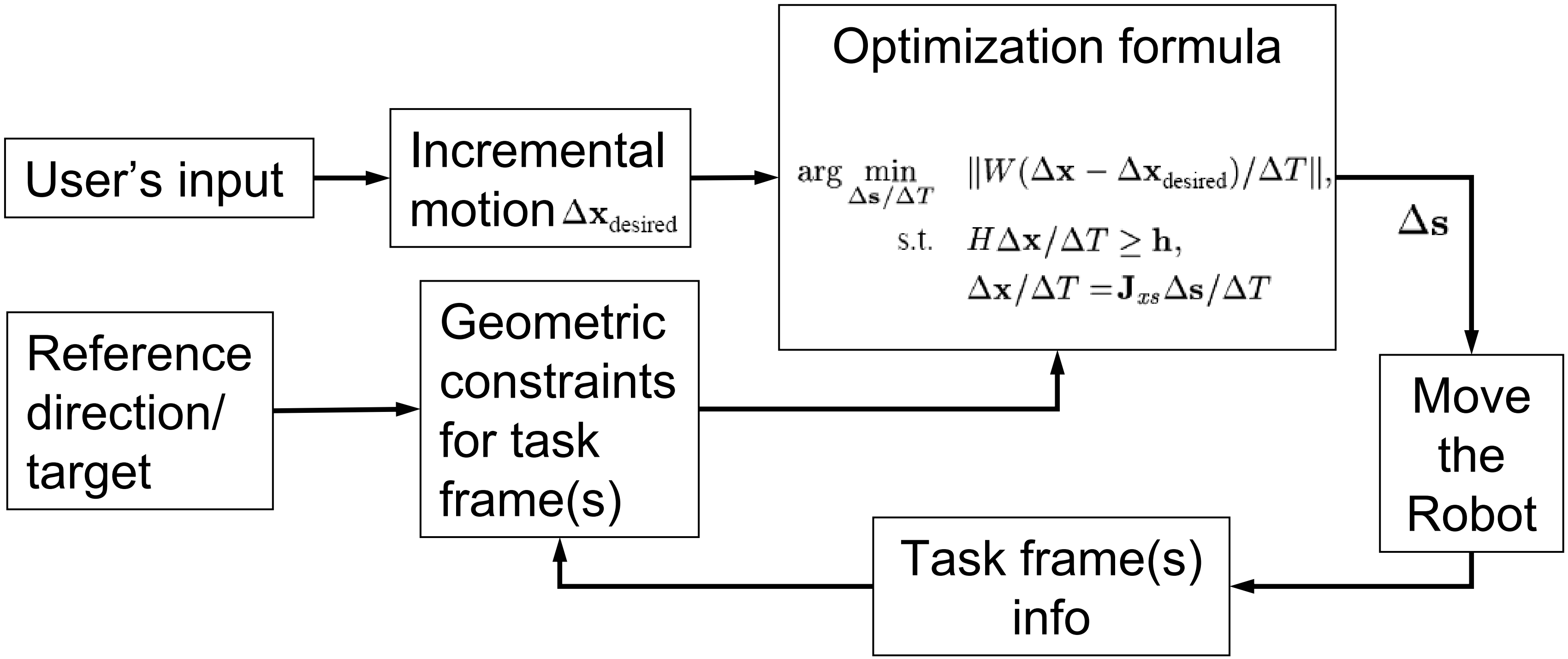
Angles L and related to backbone lengths by

$$L_i = L + r(\theta_L - \theta_0)\cos(\delta)$$

$$\dot{\mathbf{q}}_{slu} = \mathbf{J}_{l\,\psi}\,\dot{\boldsymbol{\psi}}; \quad \mathbf{J}_{l\,\psi} \in \mathbb{R}^{3\times 2}$$

Simaan N. et al, “*A Dexterous System for Laryngeal Surgery*,” ICRA 2004

Redundancy Resolution for Suturing



$\mathbf{s} \triangleq [\mathbf{q}_{lars}{}^t, \quad \boldsymbol{\psi}^t]^t \in \mathbb{R}^8$ = Augmented state vector (LARS + Snake)

$\boldsymbol{\psi} \triangleq (\theta_L, \quad \delta)^t$ = Configuration vector of the SLU

$\dot{\mathbf{q}}_{slu} = \mathbf{J}_{l\psi}\dot{\boldsymbol{\psi}} \in \mathbb{R}^3$ = Joint variables of the SLU

Minimizing tissue tear

- We want…

$$\arg\min_{\dot{\mathbf{x}}} \left\| \mathbf{W}_g \left(\dot{\mathbf{x}}_g^w - \dot{\mathbf{x}}_g^w{}_{\text{desired}} \right) \right\|$$ ← Satisfy suturing task

$$\text{s.t.} \quad \left\| \mathbf{p}_g^w - \mathbf{p}_g^w{}_{\text{start}} \right\| \leq \epsilon_g$$ ← Needle center errors

Minimizing tissue tear

- A linear approximation…

$$\mathbf{M}\left(\mathbf{p}_g^w - \mathbf{p}_{g\ \text{start}}^w\right) \leq \epsilon_g \mathbf{e}$$ where $$\mathbf{M} = \begin{bmatrix} & \vdots & \\ \cos(\eta_i)\sin(\xi_j), & \sin(\eta_i)\sin(\xi_j), & \cos(\xi_j) \\ & \vdots & \end{bmatrix}$$

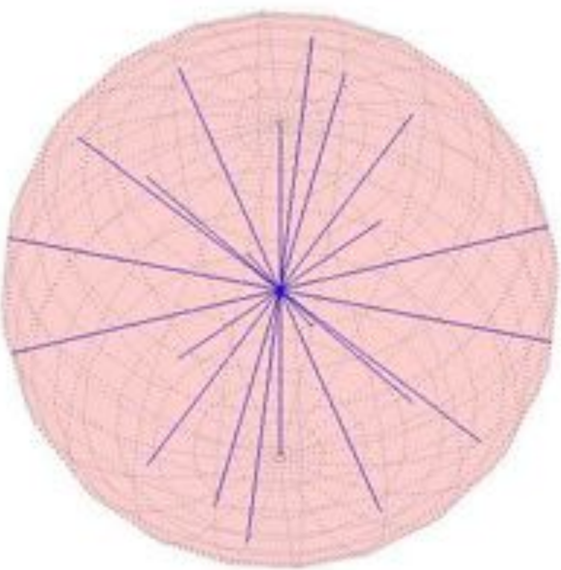
Unit vector in sphere with radius ε_g

$$\mathbf{e} = (1, \cdots, 1)^t \in \mathbb{R}^{nm}$$

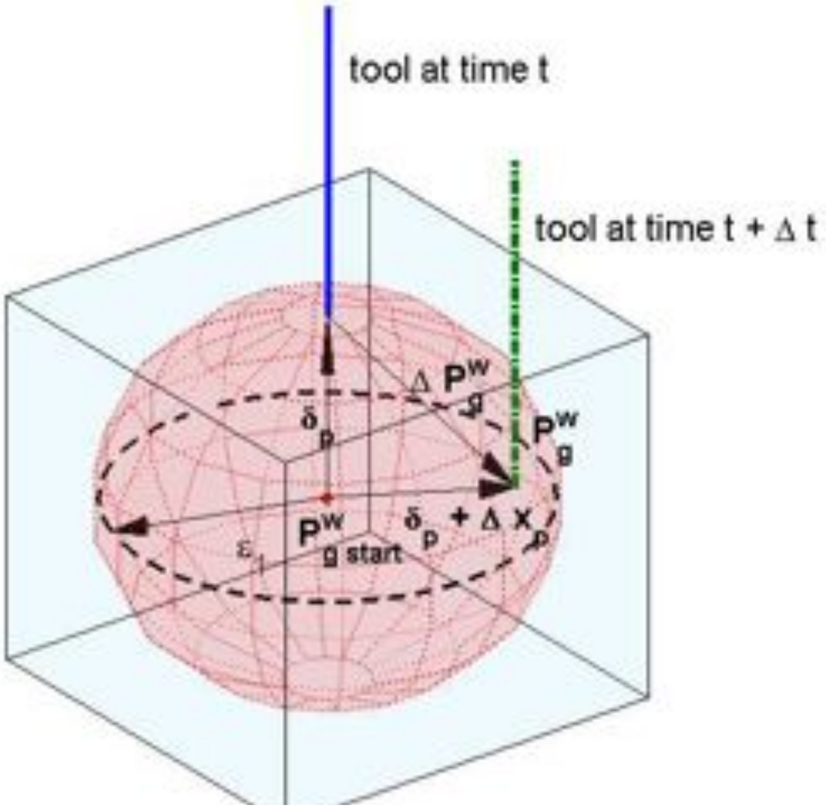
$$\eta_i = i(2\pi/n)$$

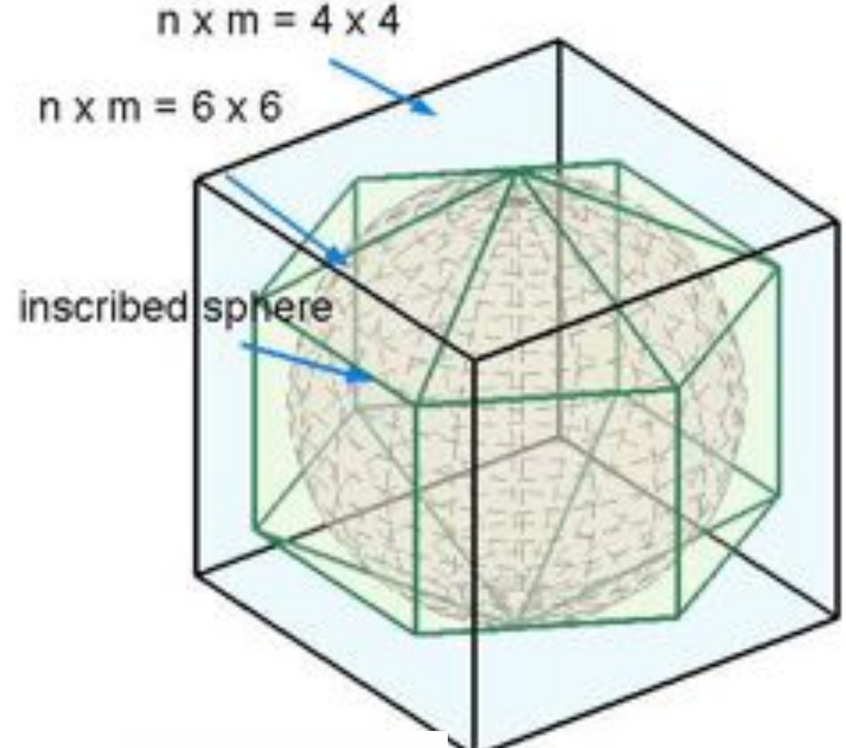
$$\xi_j = j(2\pi/n)$$

$$i = 1, \ldots, n;\ j = 1, \ldots, m$$



Minimizing tissue tear





$$\mathbf{H}_g \dot{\mathbf{p}}_g^w \geq \mathbf{h}_g$$
$$\dot{\mathbf{x}}_g^w = \mathbf{J}_{xs} \dot{\mathbf{s}}$$

where

$$\mathbf{H}_g = -\mathbf{M}$$
$$\mathbf{h}_g = -(\epsilon_g / \Delta T)\mathbf{e}$$

Avoiding joint speed limits

- SLU has actuators with limited power
- Limits the max. speed of actuations
- We want… $\dot{\mathbf{q}}_{slu\ lo} \leq \dot{\mathbf{q}}_{slu} \leq \dot{\mathbf{q}}_{slu\ up}$
- Matrix representation

$$\arg\min_{\dot{\mathbf{s}}} \quad \left\| \mathbf{W}_g \left(\dot{\mathbf{x}}_g^w - \dot{\mathbf{x}}_{g\ \text{desired}}^w \right) \right\|$$

$$\text{s.t.} \quad \mathbf{H}_t \dot{\mathbf{q}}_{slu} \geq \mathbf{h}_t$$

$$\dot{\mathbf{x}}_g^w = \mathbf{J}_{xs} \dot{\mathbf{s}}$$

where

$$\mathbf{H}_t = \left(\mathbf{I}, \quad -\mathbf{I} \right)^t \in \mathbb{R}^{6\times3}$$

$$\mathbf{h}_t = \left(\dot{\mathbf{q}}_{slu\ lo}, \quad -\dot{\mathbf{q}}_{slu\ up} \right)^t \in \mathbb{R}^6$$

$$\dot{\mathbf{q}}_{slu} = \mathbf{J}_{l\ \psi} \dot{\boldsymbol{\psi}}; \quad \mathbf{J}_{l\ \psi} \in \mathbb{R}^{3\times2}$$

Avoiding joint limits

- Finally we want… $\mathbf{s}_L \triangleq \mathbf{s}_{lo} - \mathbf{s} \leq \dot{\mathbf{s}}\,\Delta T \leq \mathbf{s}_{up} - \mathbf{s} \triangleq \mathbf{s}_U$
- In addition we want… $\arg\min_{\dot{\mathbf{s}}} \left\|\mathbf{W}_s \dot{\mathbf{s}}\right\|$
- Matrix representation

$$\arg\min_{\dot{\mathbf{s}}} \left\|\mathbf{W}_s \dot{\mathbf{s}}\right\|$$

s.t. $\mathbf{H}_s \dot{\mathbf{s}} \geq \mathbf{h}_s$

where

$$\mathbf{H}_s = \left(\mathbf{I}, \quad -\mathbf{I}\right)^t \in \mathbb{R}^{16\times 8}$$

$$\mathbf{h}_s = \left(\mathbf{s}_L/\Delta T, \quad \mathbf{s}_U/\Delta T\right)^t \in \mathbb{R}^{16}$$

Optimization Algorithm

Step 1: Describe a desired incremental motion $\Delta \mathbf{x}_{\text{desired}}$ of the instrument based on user's inputs.

Step 2: Use the robot instantaneous kinematic equations to produce a linearized optimization problem,

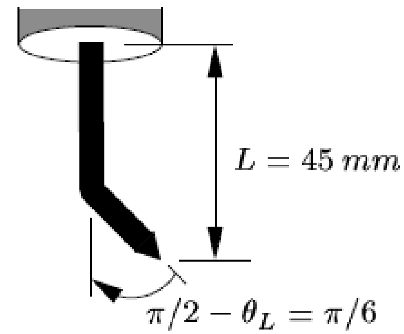
$$\arg\min_{\dot{\mathbf{s}}} \left\| \begin{bmatrix} \mathbf{W}_g & \mathbf{0} \\ \mathbf{0} & \mathbf{W}_s \end{bmatrix} \left(\begin{bmatrix} \mathbf{J}_{xs} \\ \mathbf{I} \end{bmatrix} \dot{\mathbf{s}} - \begin{bmatrix} \dot{\mathbf{x}}_{g\ \text{desired}}^{w} \\ \mathbf{0} \end{bmatrix} \right) \right\|$$

$$\text{s.t.} \begin{bmatrix} \mathbf{H}_g & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{H}_t & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{H}_s \end{bmatrix} \begin{bmatrix} \mathbf{J}_v \\ \begin{bmatrix} \mathbf{0} & \mathbf{J}_{l\psi} \end{bmatrix} \\ \mathbf{I} \end{bmatrix} \dot{\mathbf{s}} \geq \begin{bmatrix} \mathbf{h}_g \\ \mathbf{h}_t \\ \mathbf{h}_s \end{bmatrix}$$

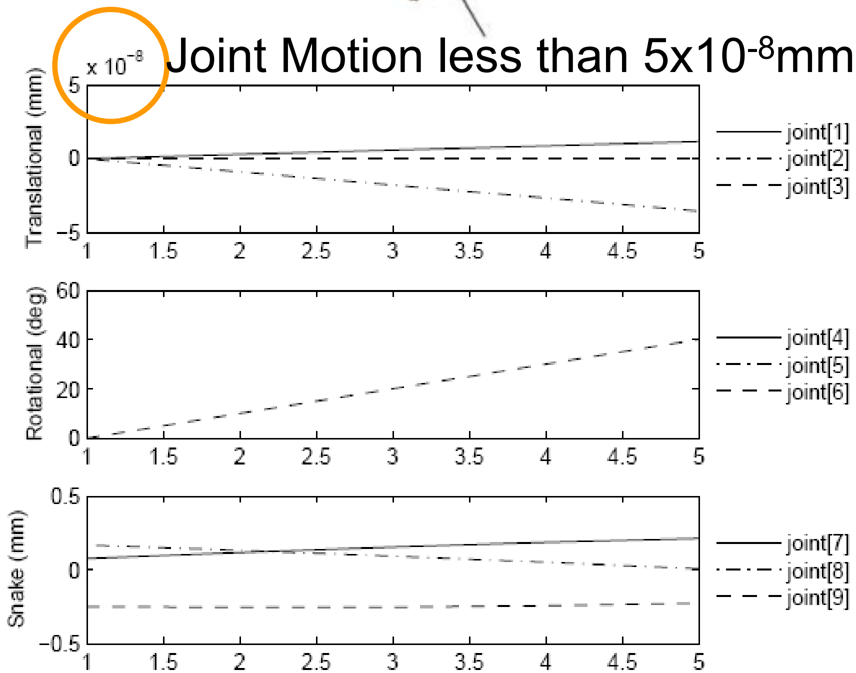
Step 3: Use known numerical methods to compute incremental joint motions $\Delta \mathbf{s}$ and use these results to move the robot. [Lawson and Hanson’s method]

Step 4: Go back to Step 1.

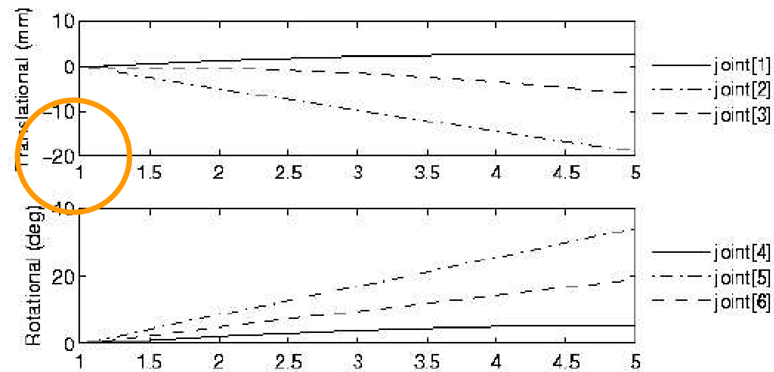
Comparing Proximal Joint Motion



Joint Motion less than $5x10^{-8}$mm



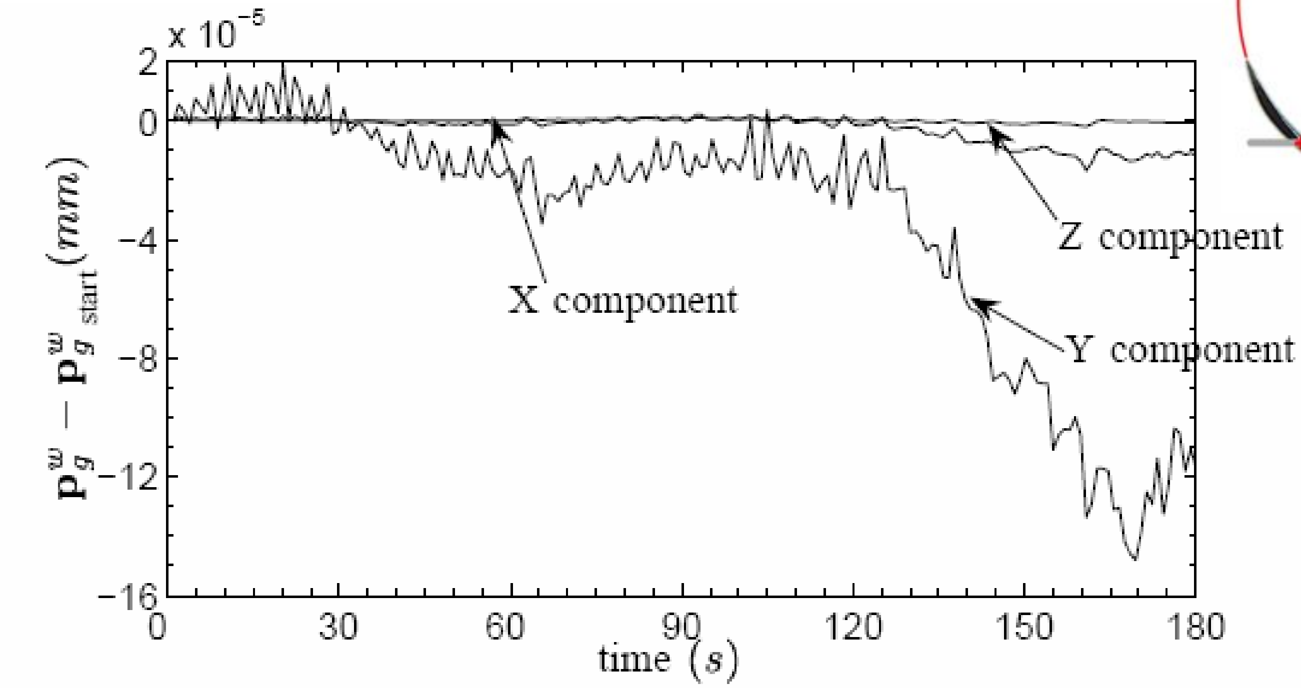
Max Joint Motion around 20mm

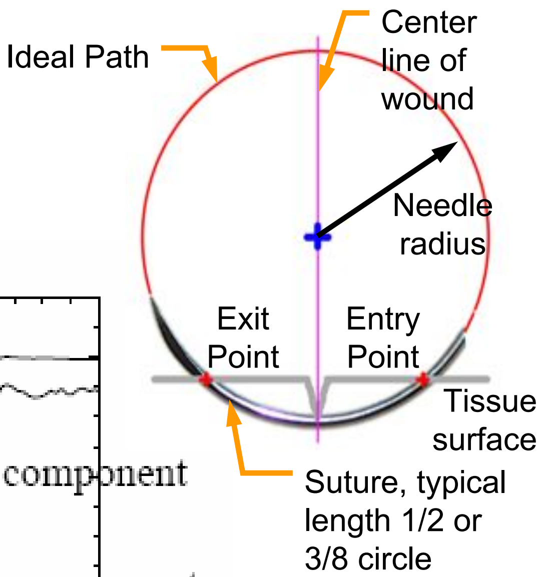


Distal dexterity provided by SLU helps in avoiding proximal joint motion during suturing

Results – Actual vs Ideal Paths

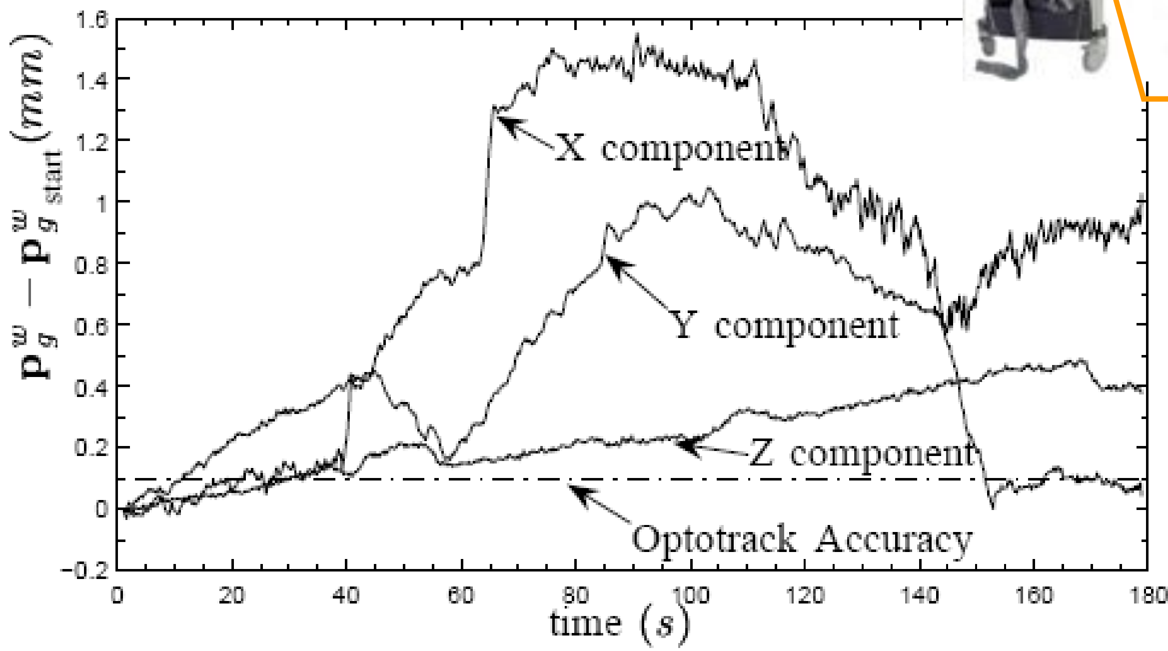
Using Robot Encoders and Kinematics
Center of Suture with a sphere of 1.4um



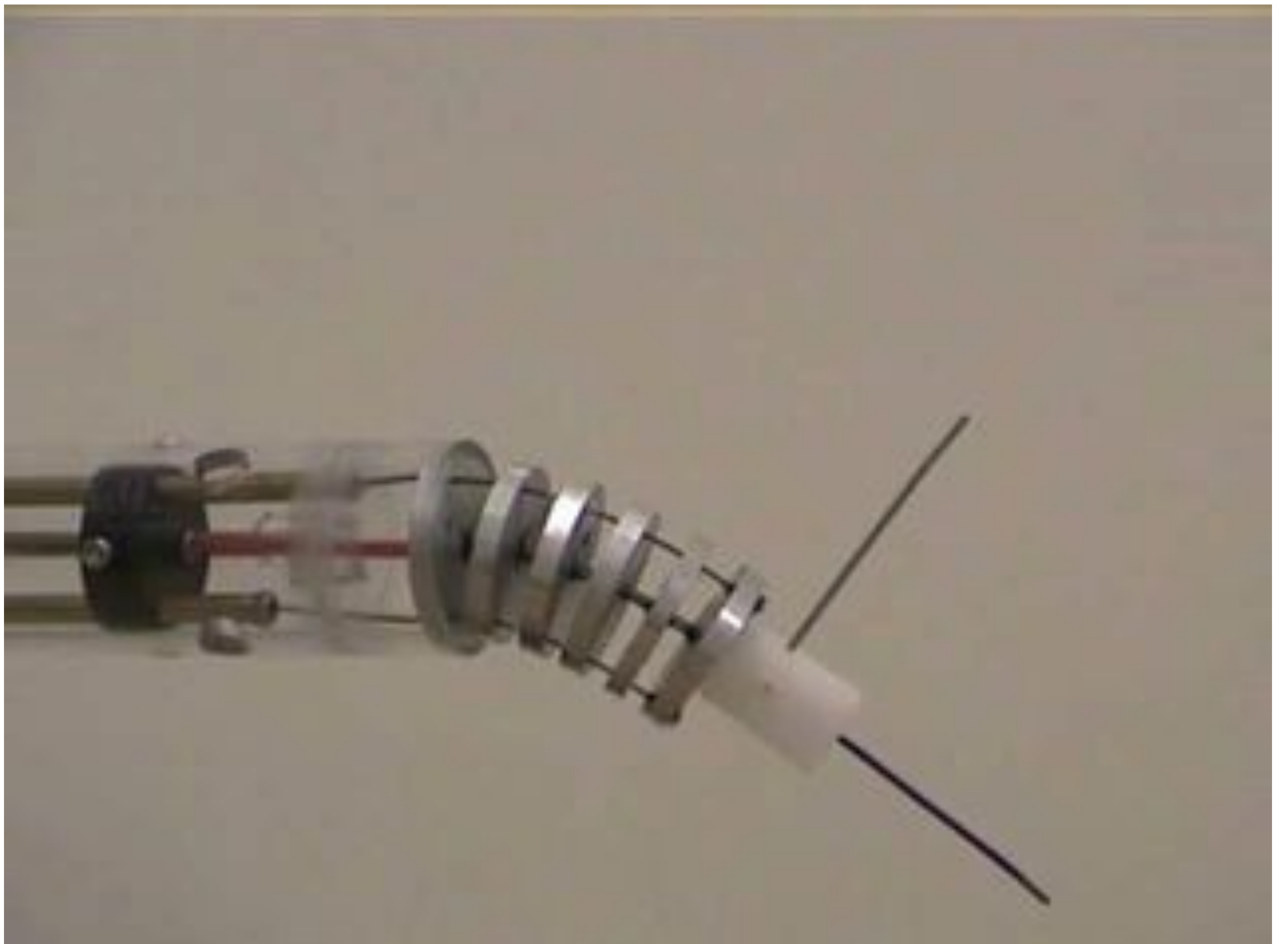


Results – External Measurements

Using OptoTrak - Optical Measuring Device
Center of Suture with a sphere of 1.84mm



Results - Movie



Future Work

Suturing using the “Steady Hand Robot”

To appear in Intl. Conf. on Medical Image Computing and Computer Assisted Intervention, CA, USA, Oct 2005

Conclusions

- Developing and testing the high-level control for a future tele-robotic system for MIS of the throat and upper airways.
- Extendable to include additional constraints such as collision avoidance, anatomic-based constraints [Li ‘03]
- Suturing motion can be accomplished with minimal motion of proximal joints if SLU is used.
- Validation of kinematic model of SLU.

Li ’05: Li M., and Taylor R. H., *Spatial Motion Constraints in Medical Robot Using Virtual Fixtures Generated by Anatomy*, ICRA, 2003

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Questions?