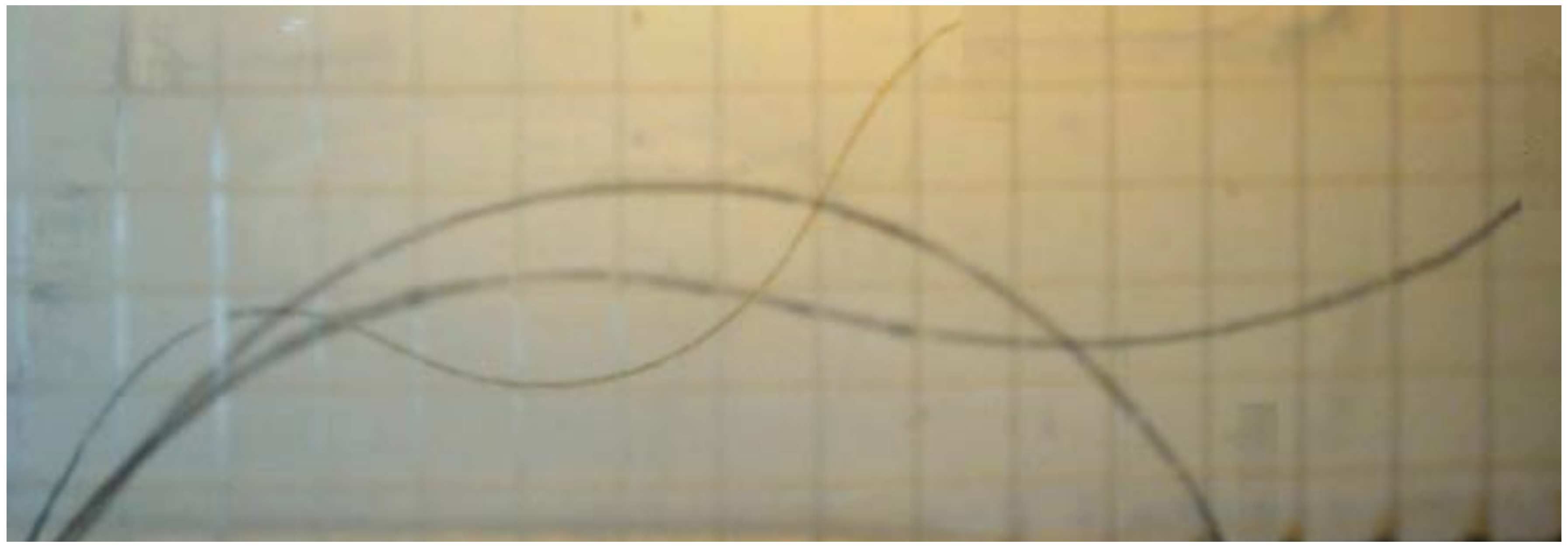
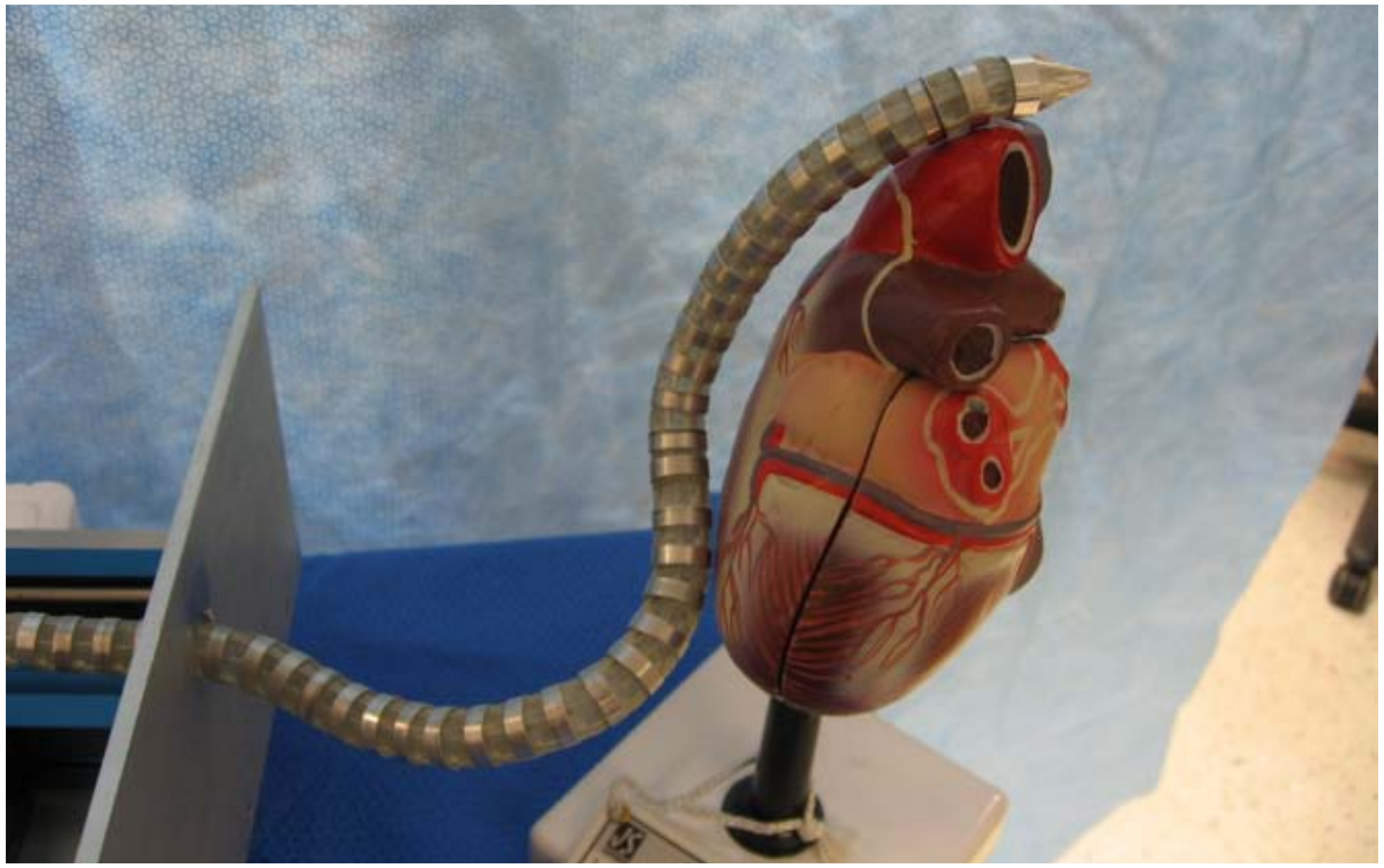
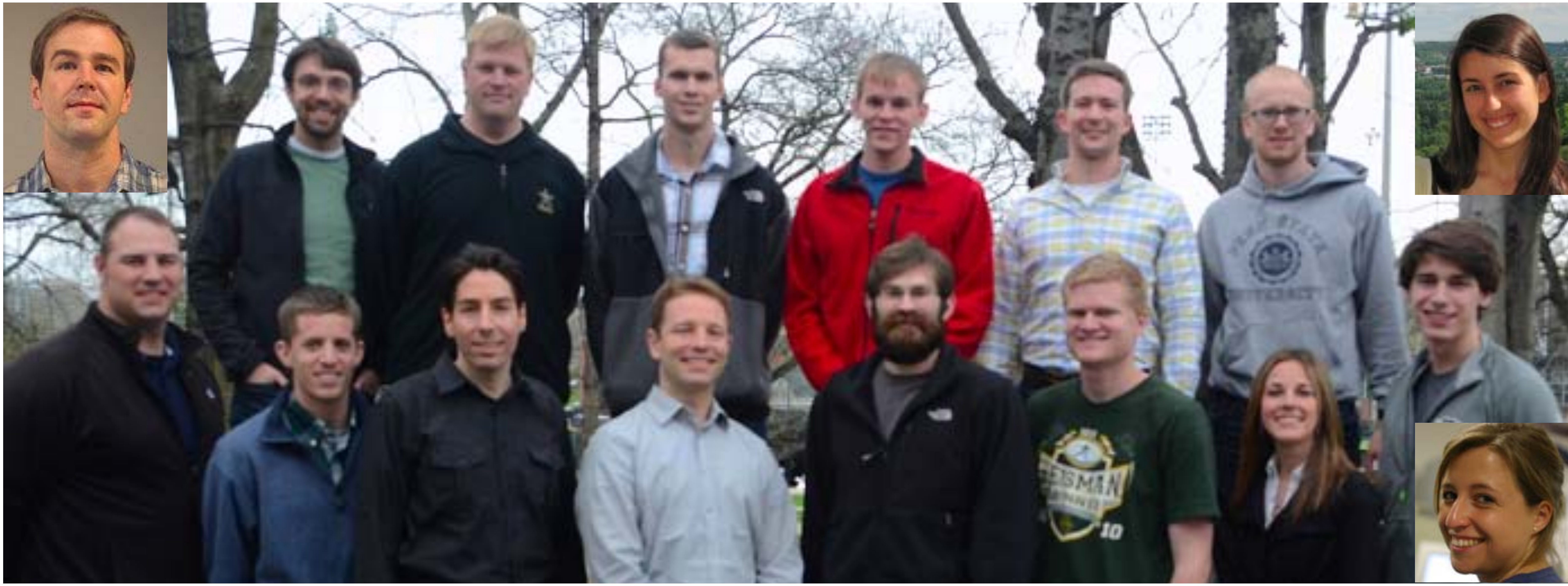




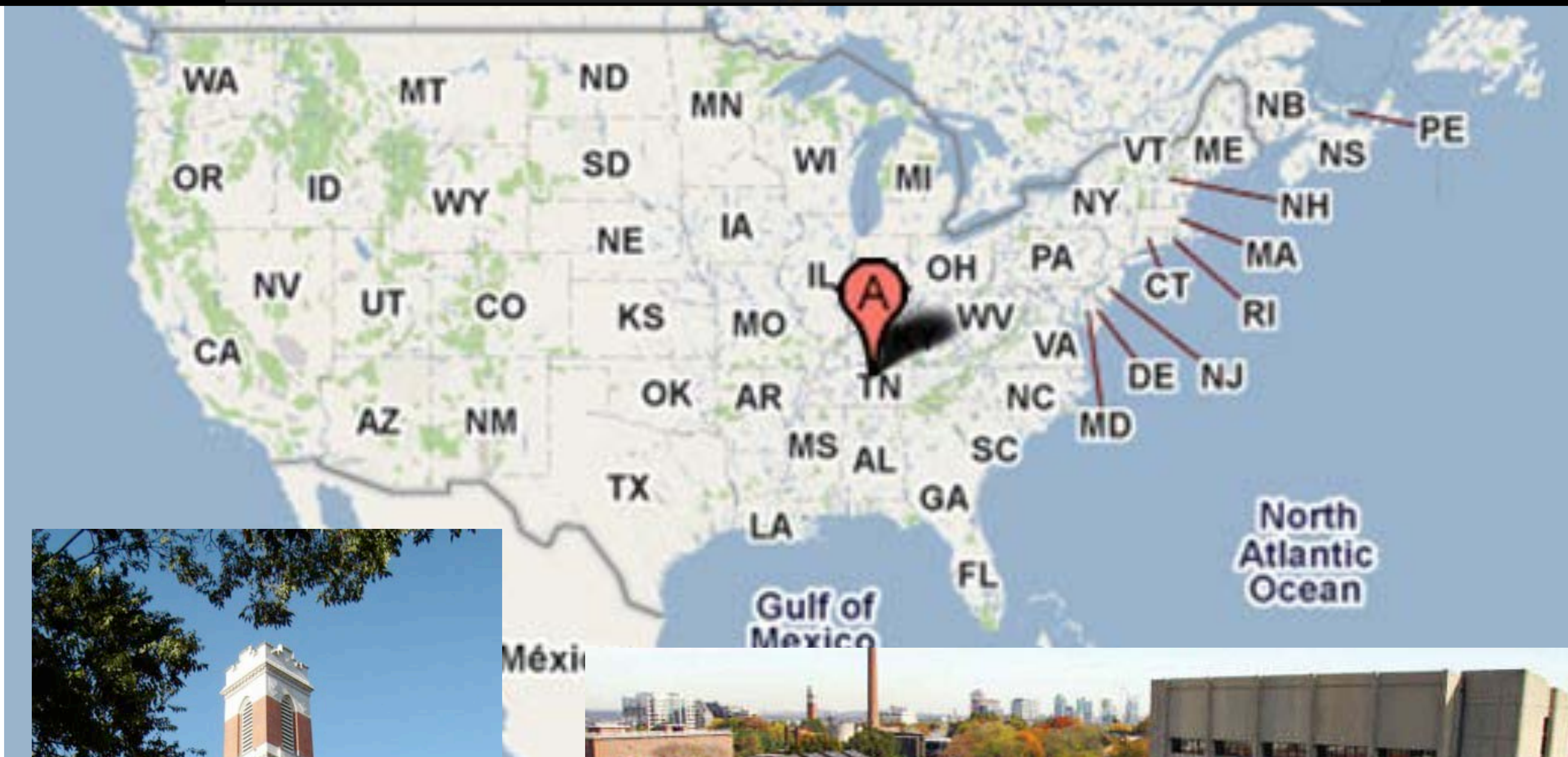

So You Want to Build a Needle/Scope-Like Robot Where Do You Start?

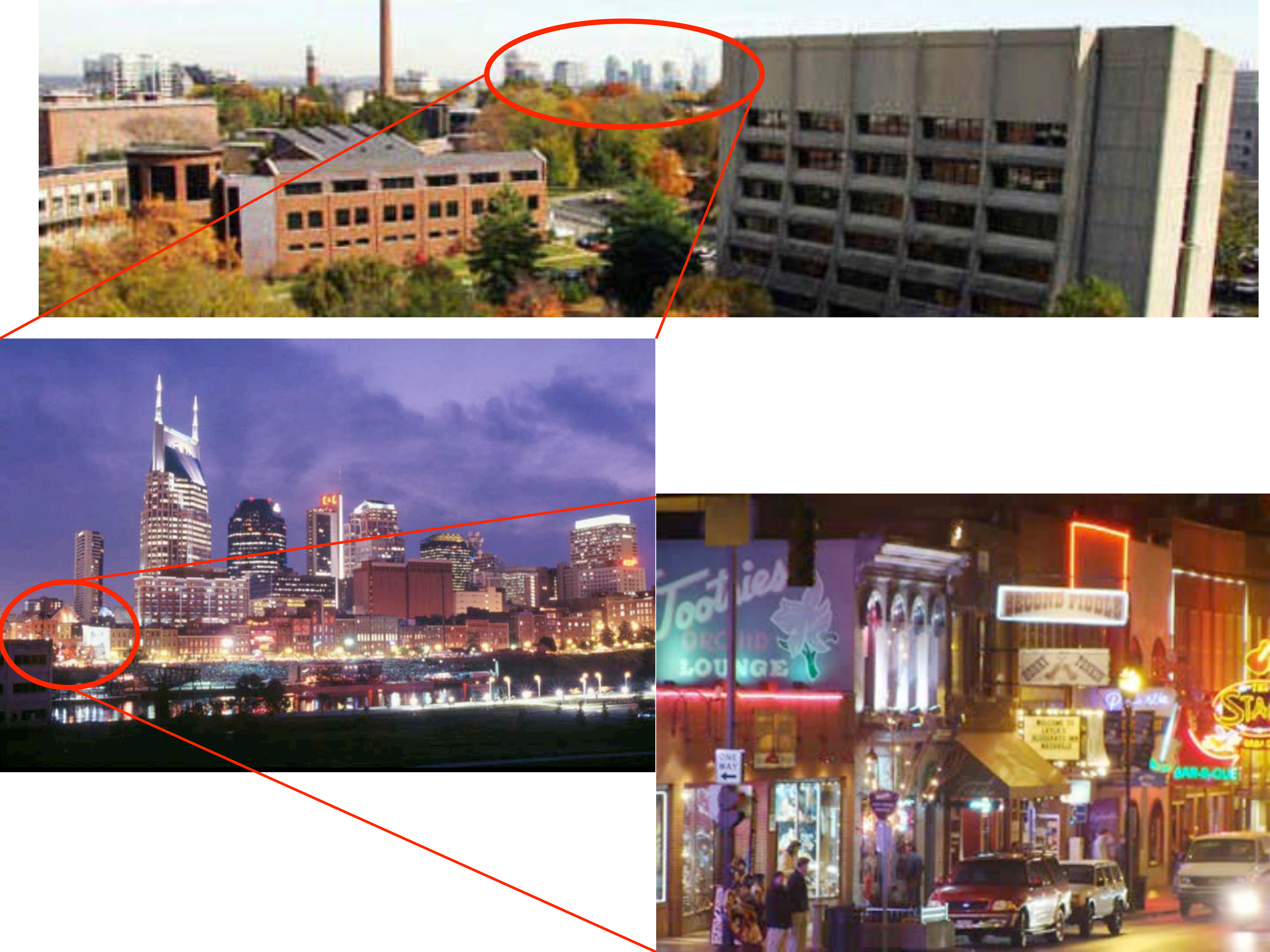
Robert J. Webster III, September 11, 2013

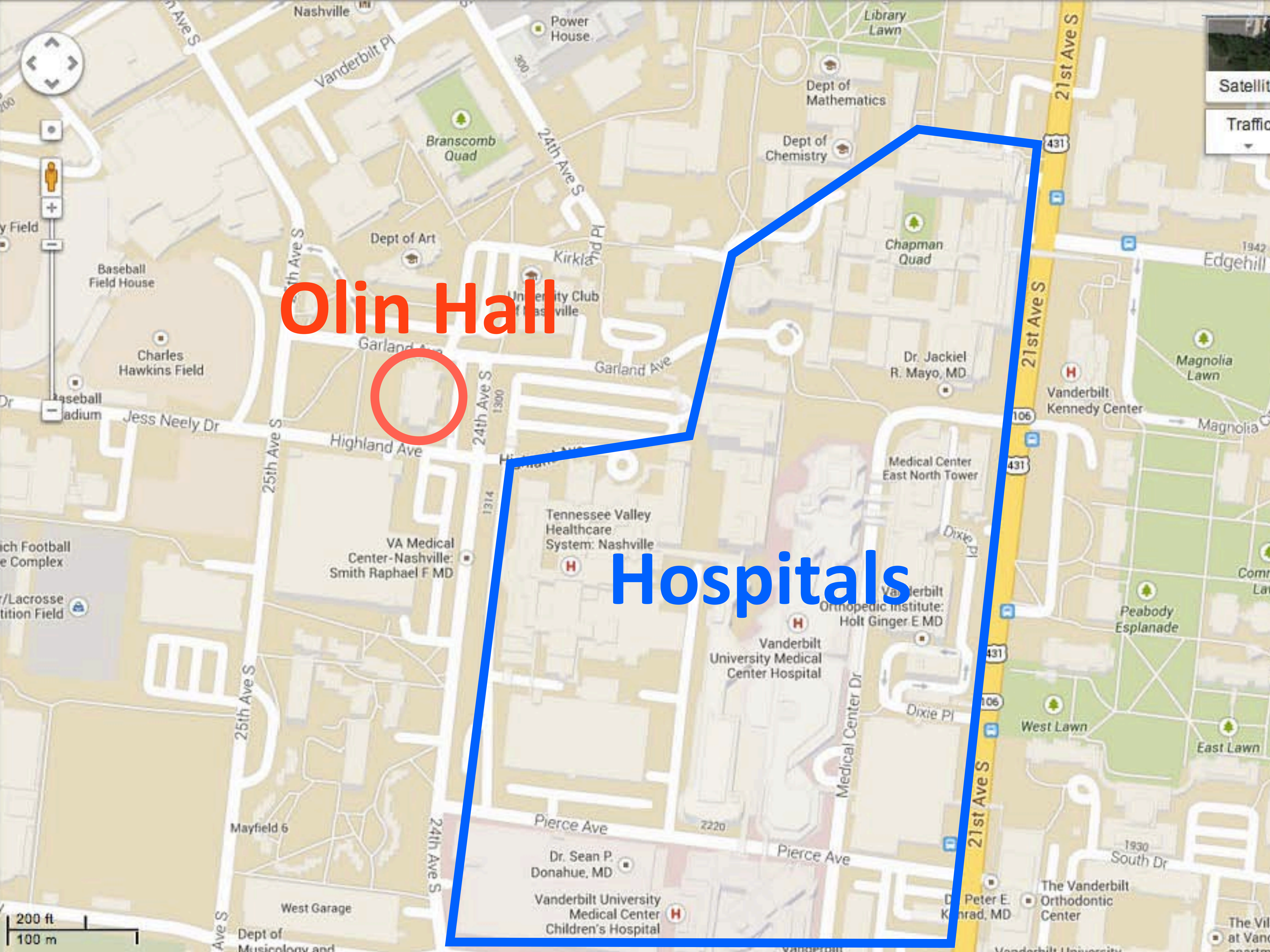
Introductions/Acknowledgements



VANDERBILT UNIVERSITY



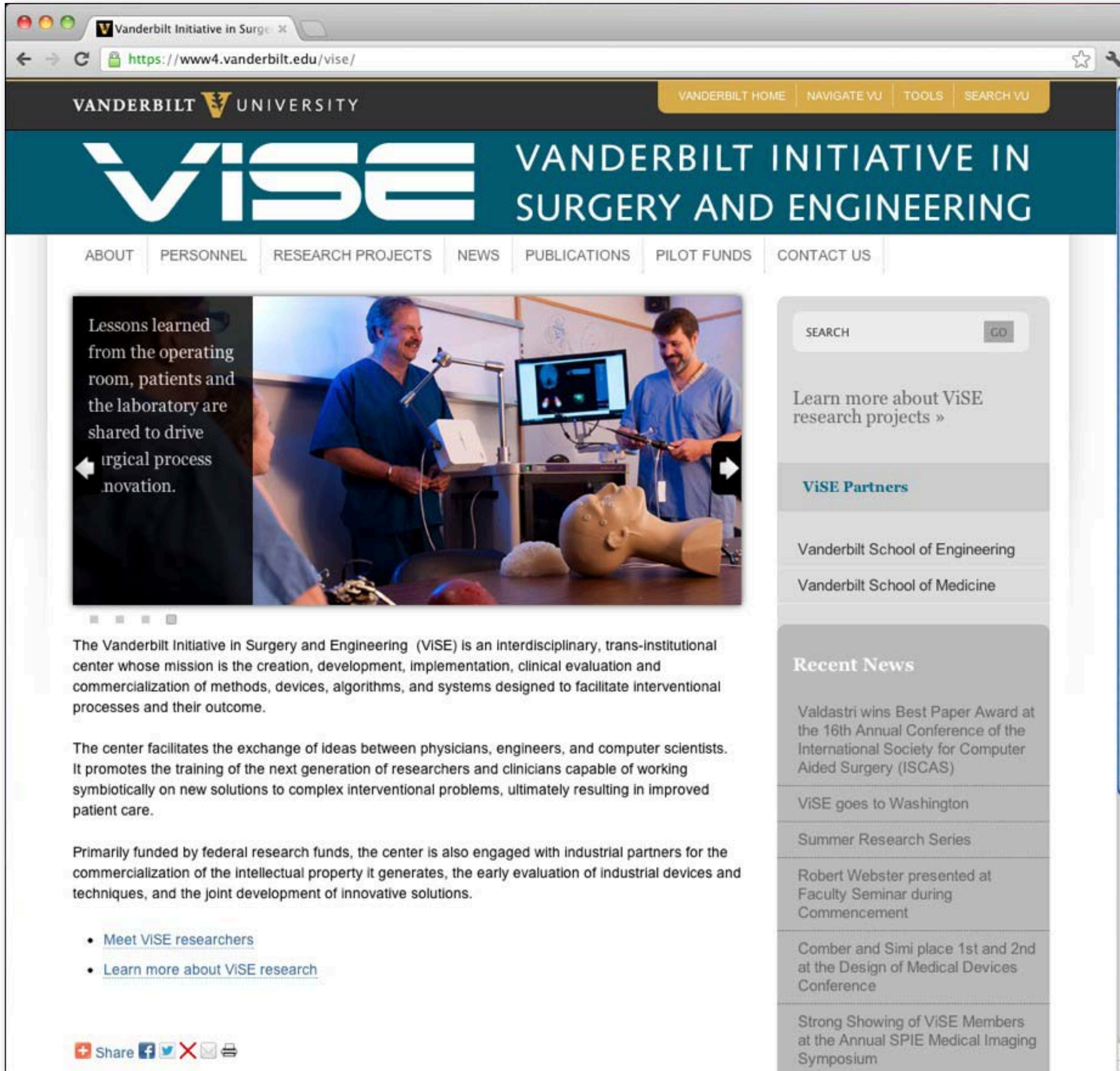

ORCHID
LOUNGE
ONE WAY



Olin Hall
Hospitals
Nashville
Power House
Library Lawn
Vanderbilt Pl
Dept of Mathematics
Branscomb Quad
Dept of Chemistry
24th Ave S
21st Ave S
Chapman Quad
Dept of Art
Kirkland Pl
Baseball Field House
University Club of Nashville
Edgehill
Charles Hawkins Field
Garland Ave
Dr. Jackiel R. Mayo, MD
Magnolia Lawn
Vanderbilt Kennedy Center
Jess Neely Dr
Highland Ave
Magnolia
25th Ave S
Medical Center East North Tower
Tennessee Valley Healthcare System: Nashville
VA Medical Center-Nashville: Smith Raphael F MD
Dixie Pl
Vanderbilt Orthopedic Institute: Holt Ginger E MD
Peabody Esplanade
Vanderbilt University Medical Center Hospital
Medical Center Dr
West Lawn
East Lawn
Mayfield 6
Pierce Ave
South Dr
Dr. Sean P. Donahue, MD
Vanderbilt University Medical Center Children's Hospital
The Vanderbilt Orthodontic Center
West Garage
200 ft
100 m
Satellite
Traffic

Surgical Engineering at Vanderbilt

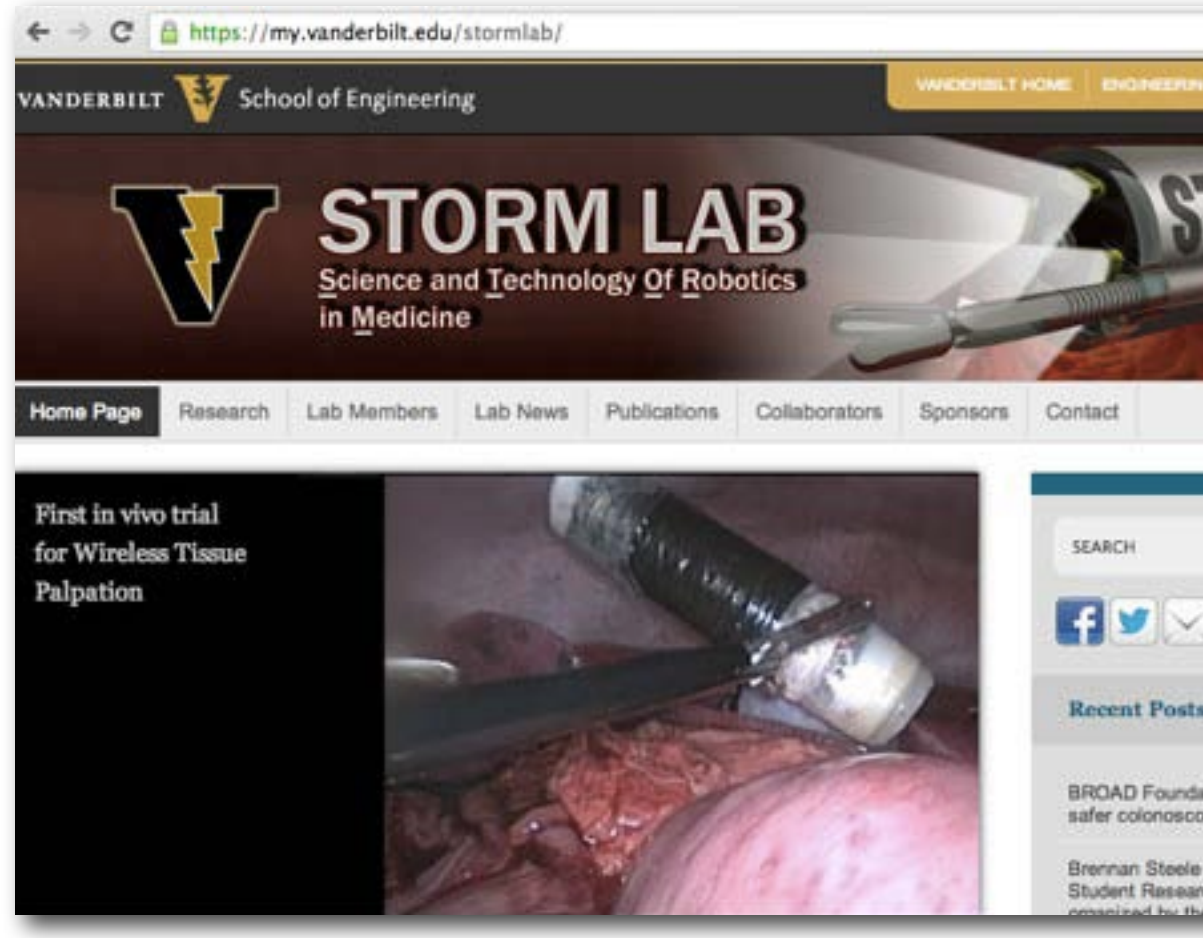
- 1.5 years old
- ~25 Faculty
- 50-50 Med/Eng
- ~$20M in Funding
- 5600 Sq Ft in Med Center + OR area
- Mission: Translational Engineering => Patient Benefits



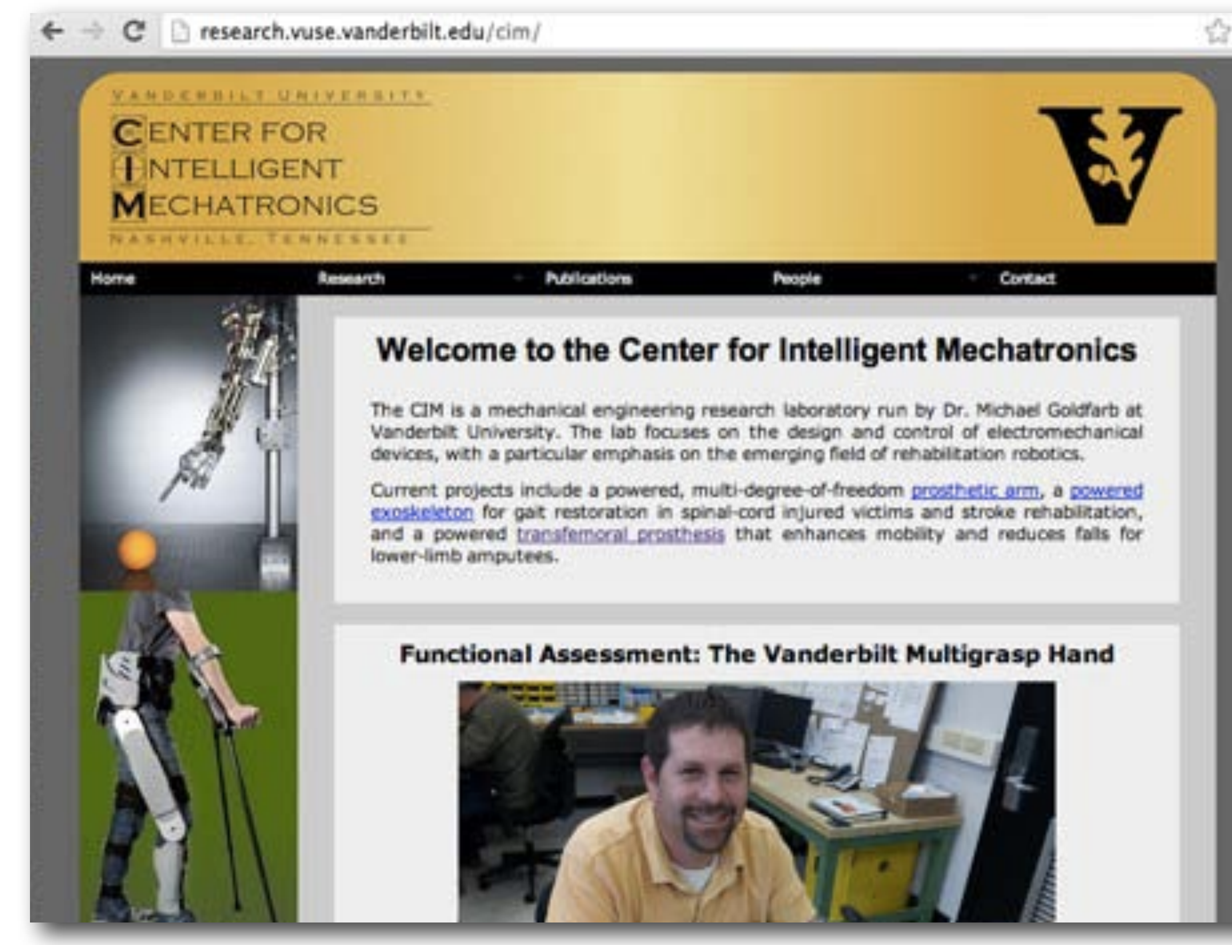
http://vanderbilt.edu/vise/

Robotics In ME at Vanderbilt

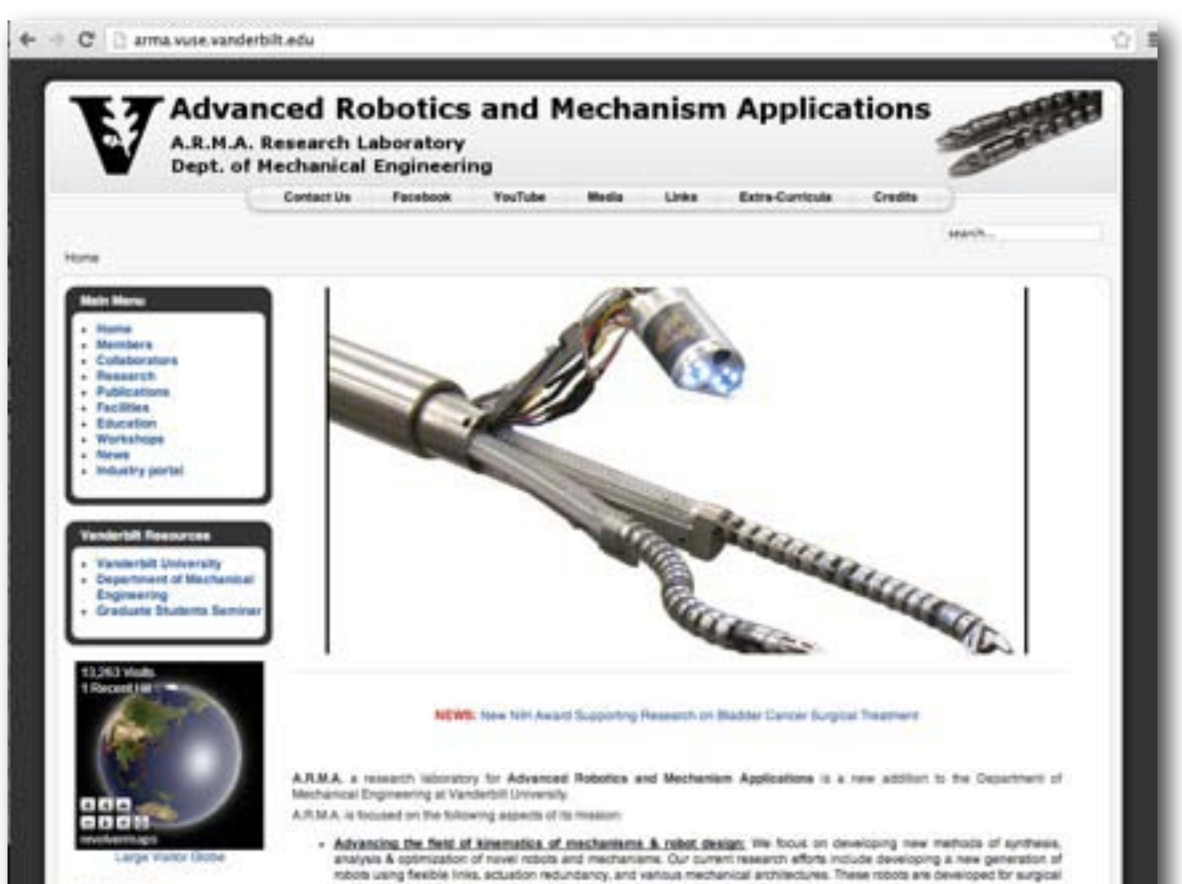
Webster



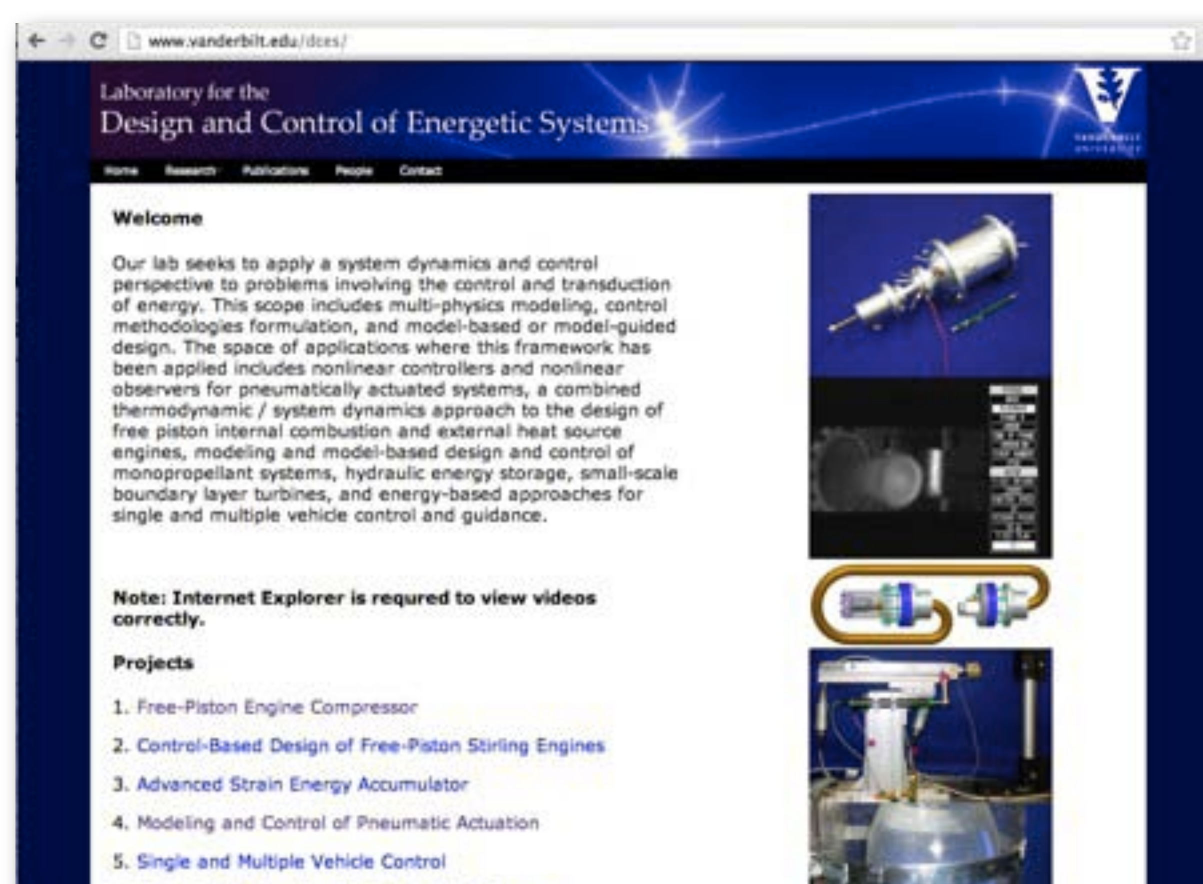
Valdastri



Goldfarb

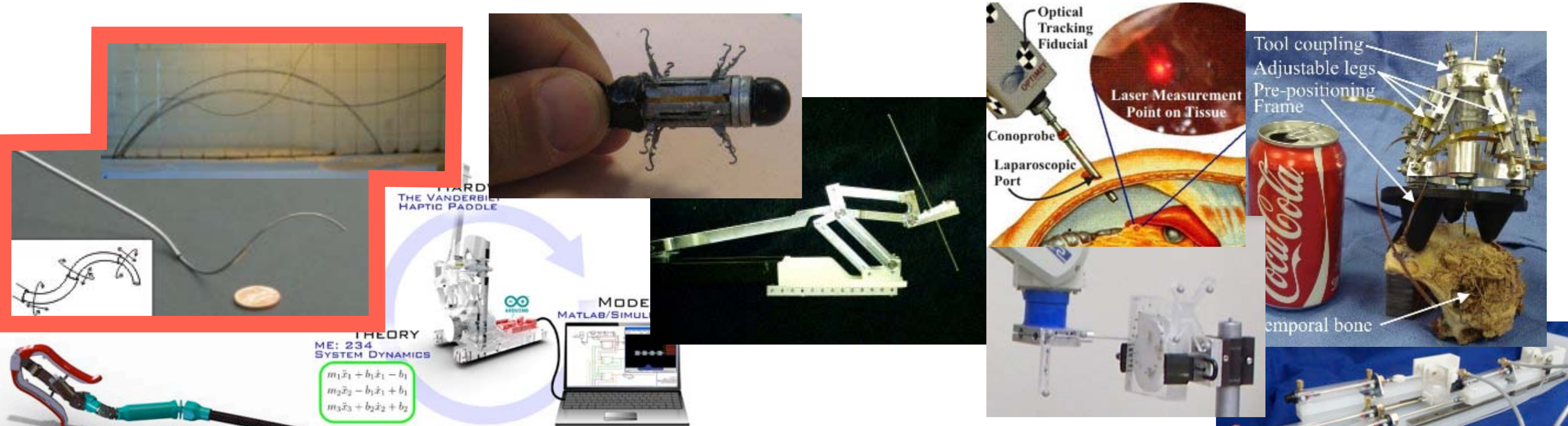


Simaan



Barth

Sarkar



Robots/Devices

Clinical Applications

Outline of This Presentation

- History
- Design
- Modeling
- Example: Concentric Tube Robot
- Example: Steerable Needle

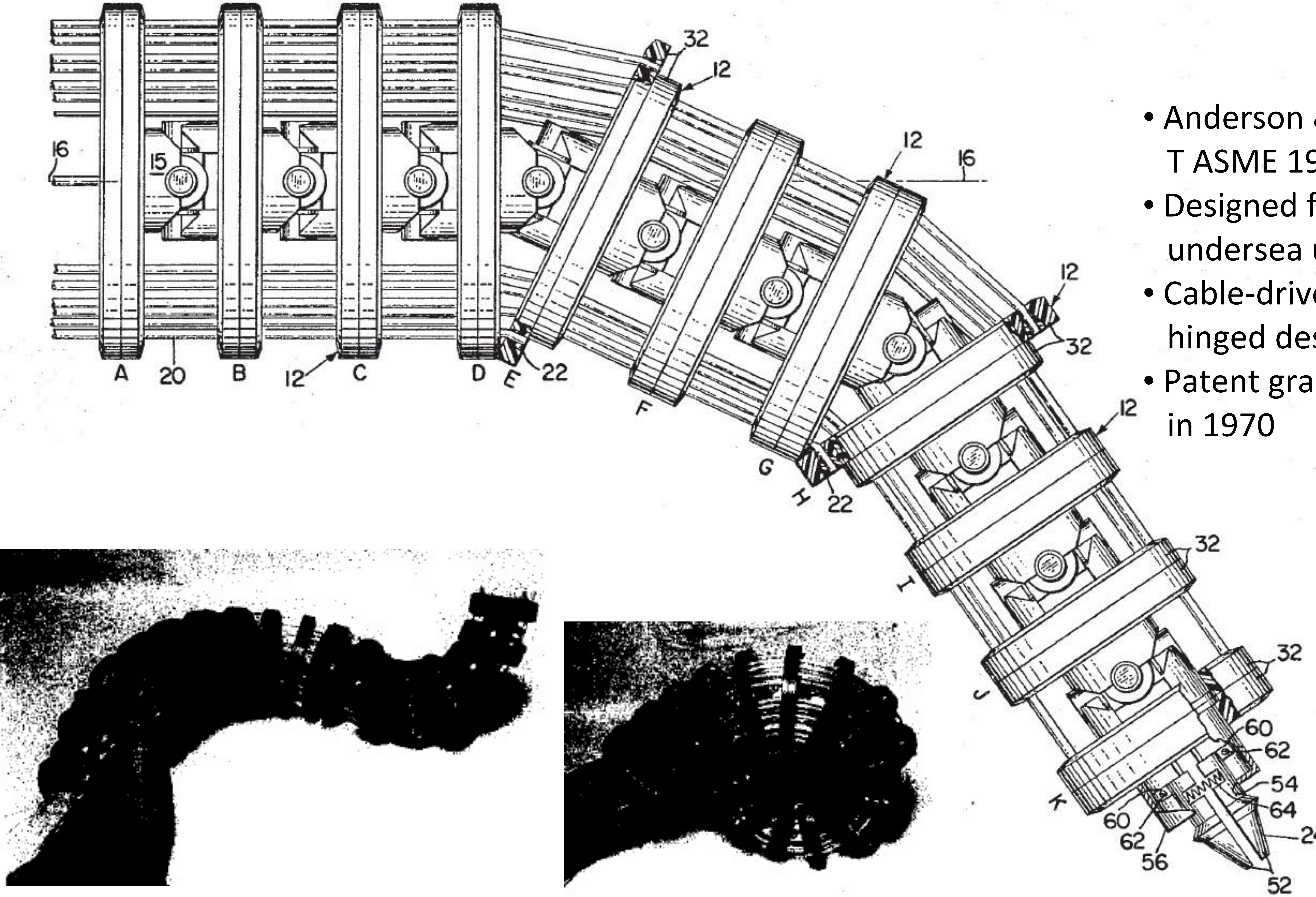
A lot of basic material that roughly follows the outline of the first 1/3 of this talk is available in:

Webster and Jones, "Design and Kinematic Modeling of Constant Curvature Continuum Robots: A Review," IJRR, 2010.

The First Continuum (actually Hyperredundant) Robot?

- The Orm (Scheinman & Leifer, circa 1965)
- One of the first computer-controlled robot arms
- Pneumatic bellows actuation
- For industrial (e.g. factory) applications
- Abandoned due to poor movement precision
- Now on display at the Computer History Museum in Mountain View, CA

The other candidate for first: The "Tensor Arm"

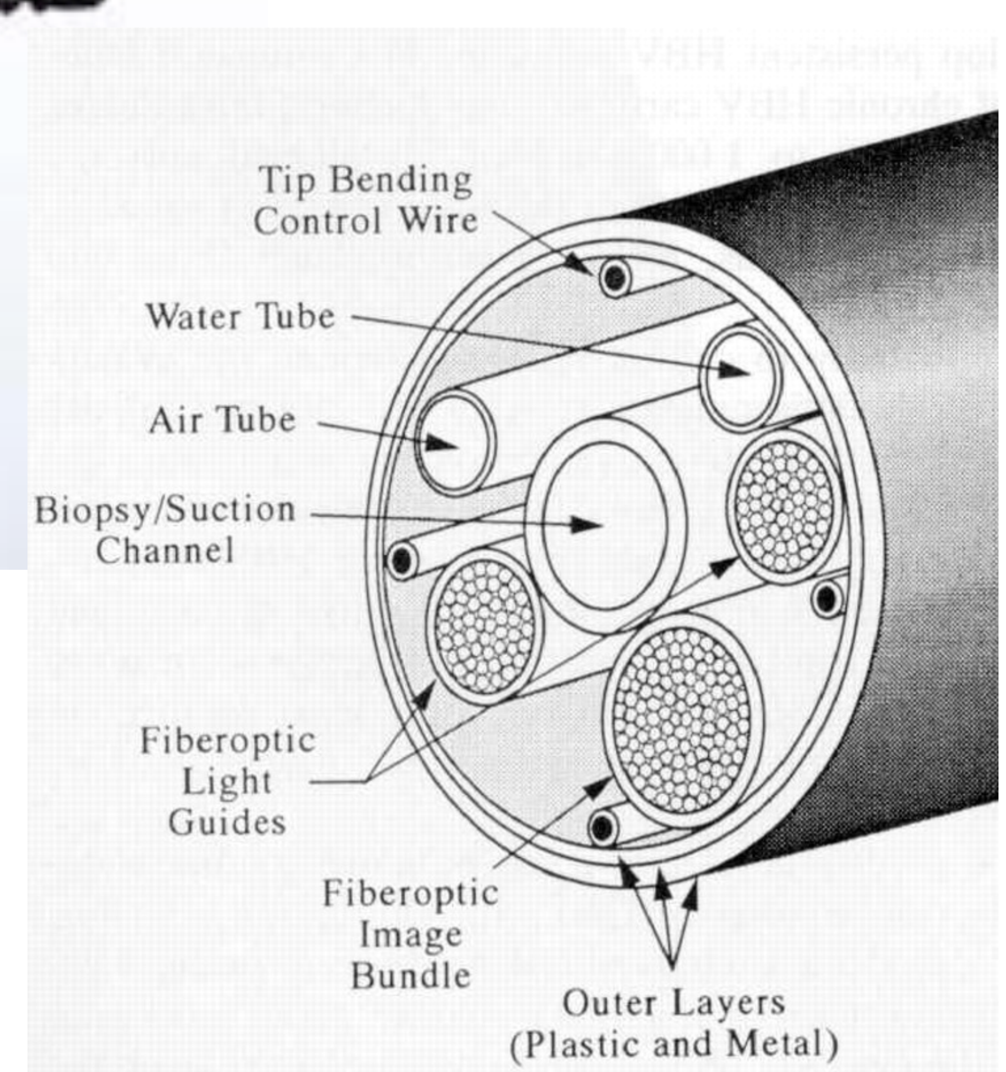


- Anderson & Horn T ASME 1967
- Designed for undersea use
- Cable-driven, hinged design
- Patent granted in 1970

The first Continuum Medical Device?

- Colononscope developed in the 1960s (catalyst: fiberoptic light sources)
- First wire-actuated version: 1970

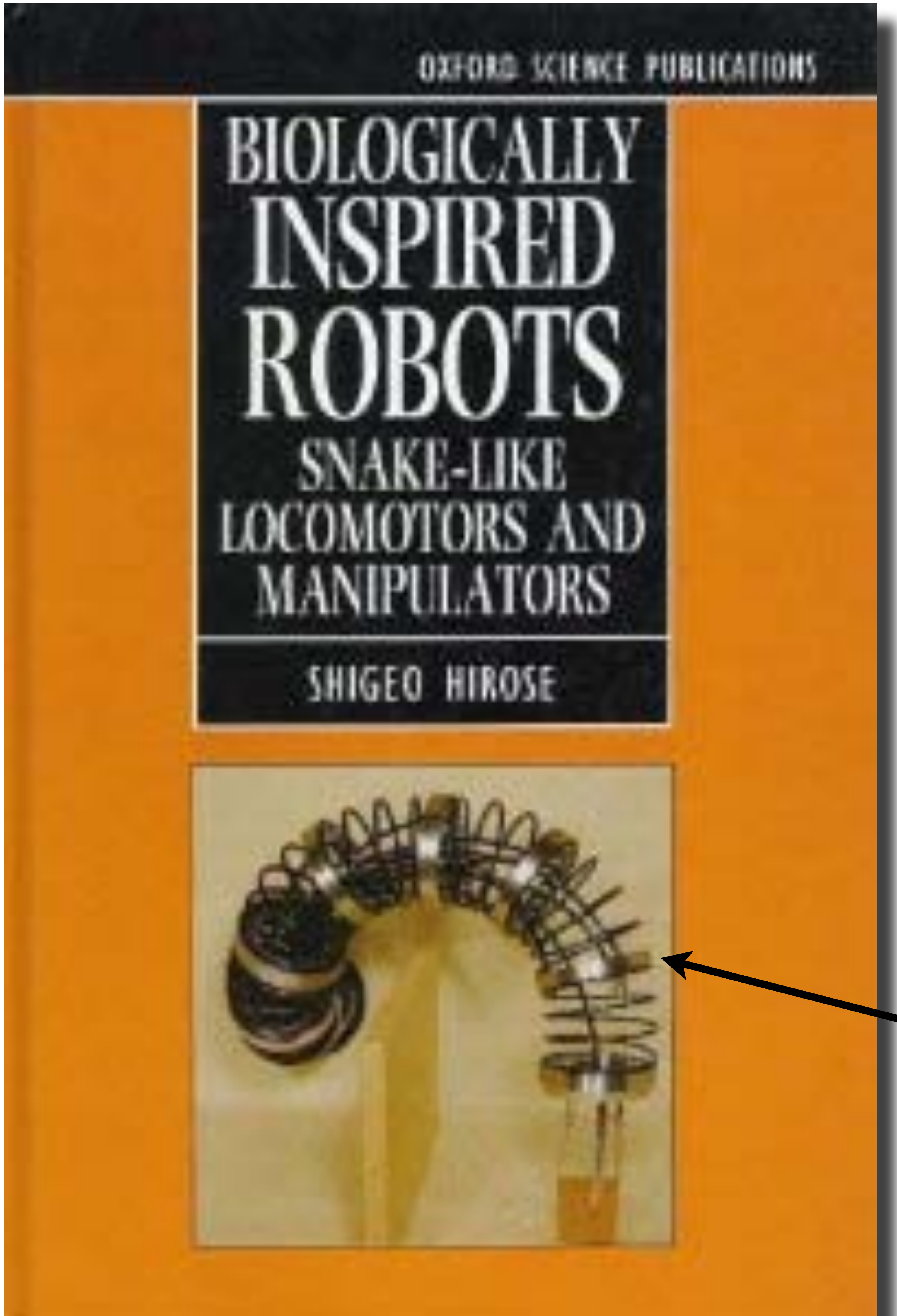
Olympus Lucera



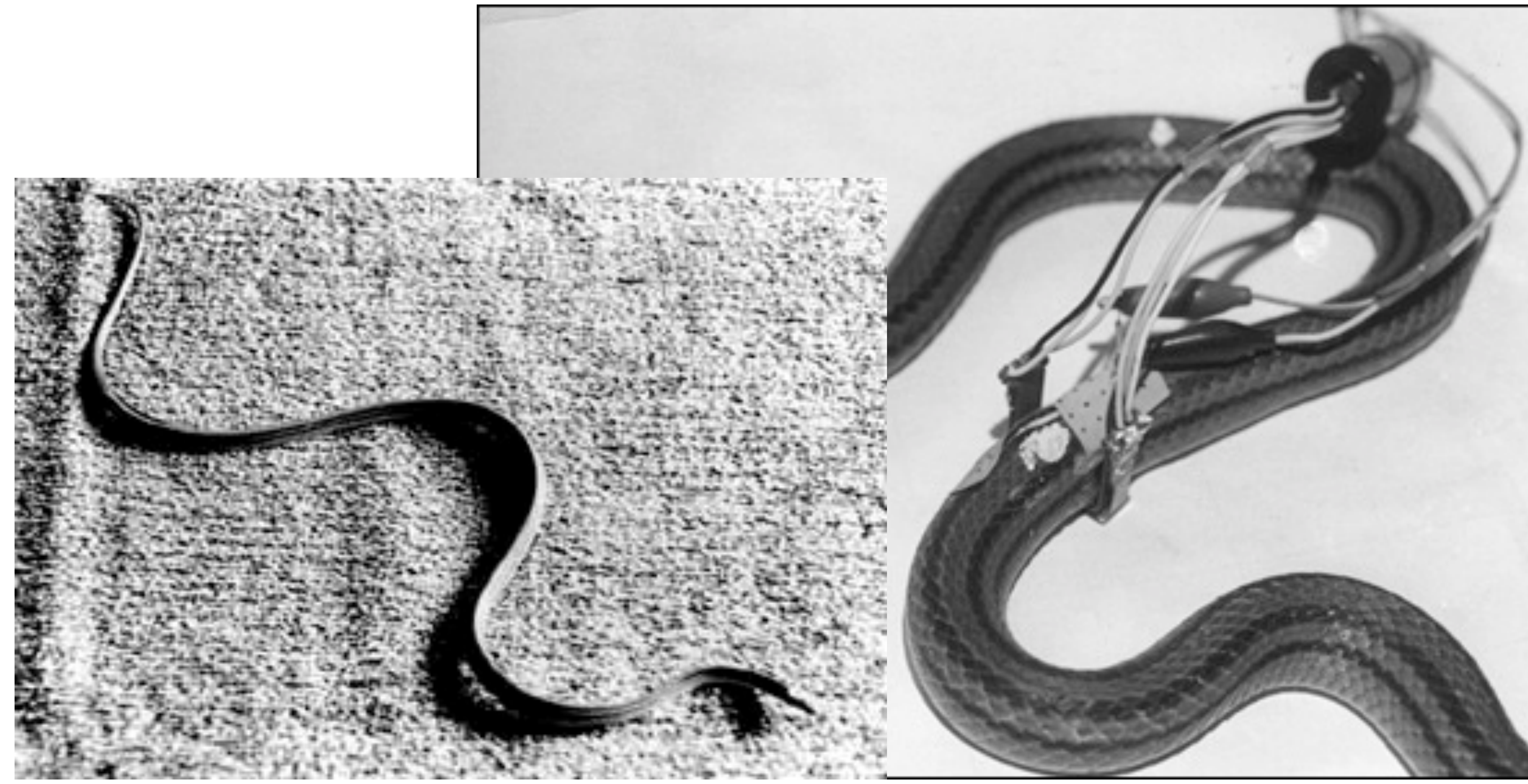
- These are manually operated continuum “robots”

Olympus Evis

Late 1970s Onward: The Era of Hirose

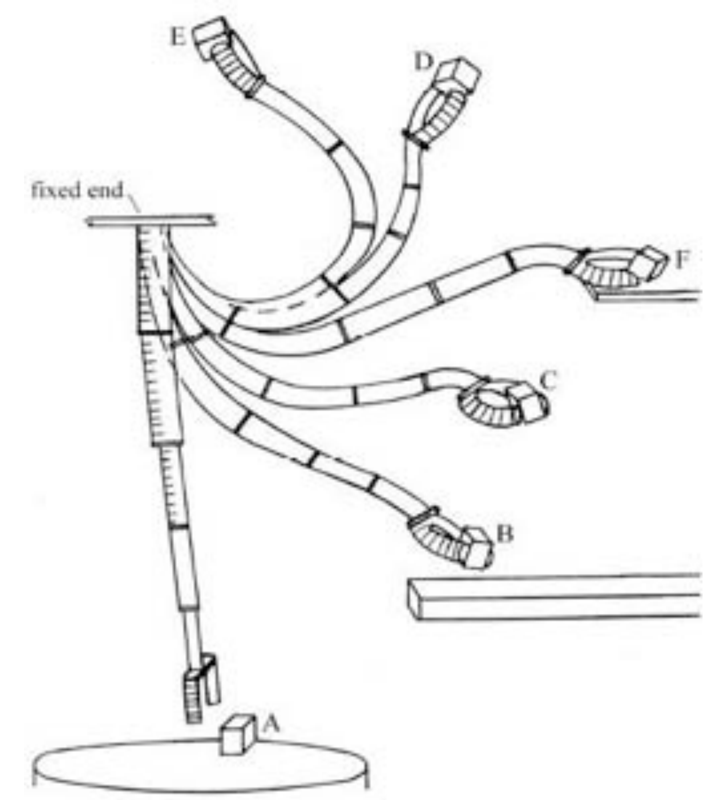


Elastor
(wire-driven
arm) 1981

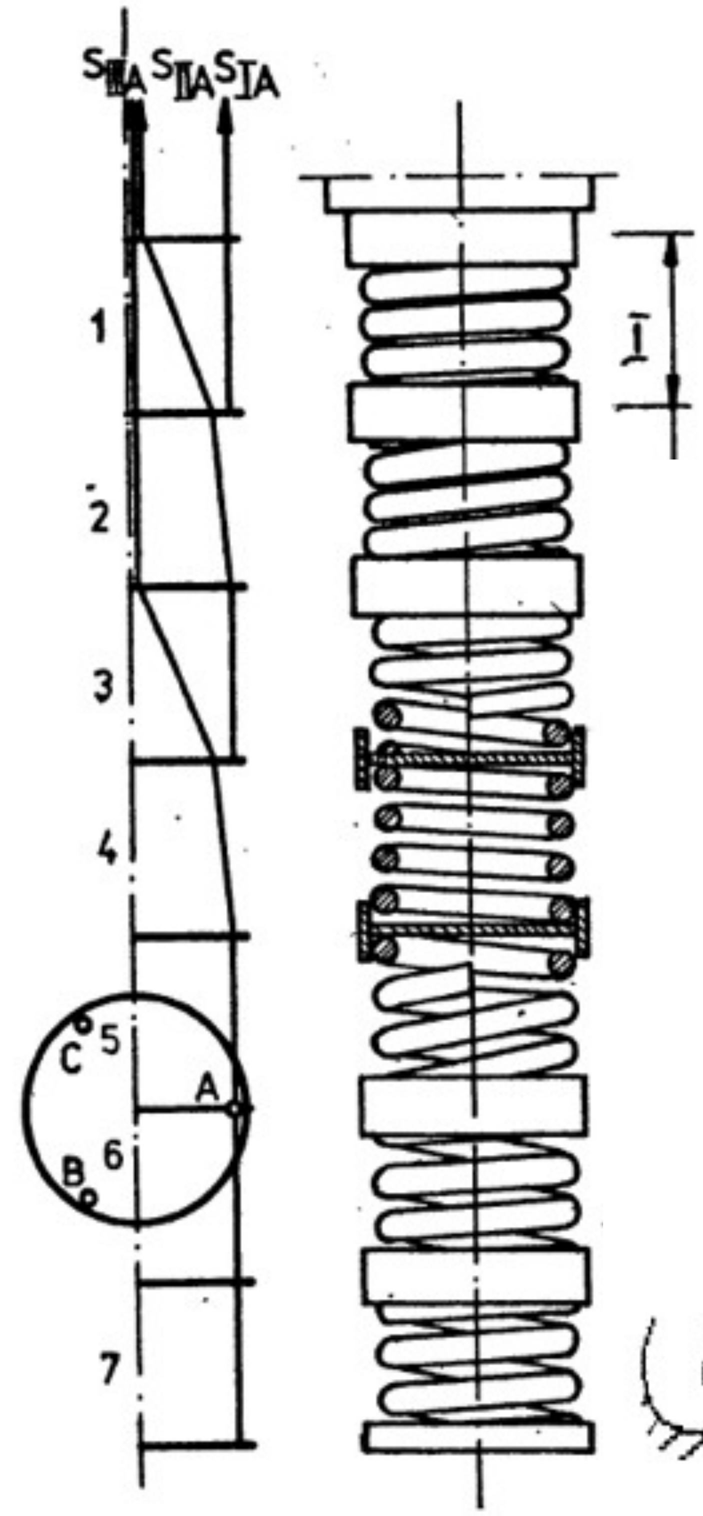


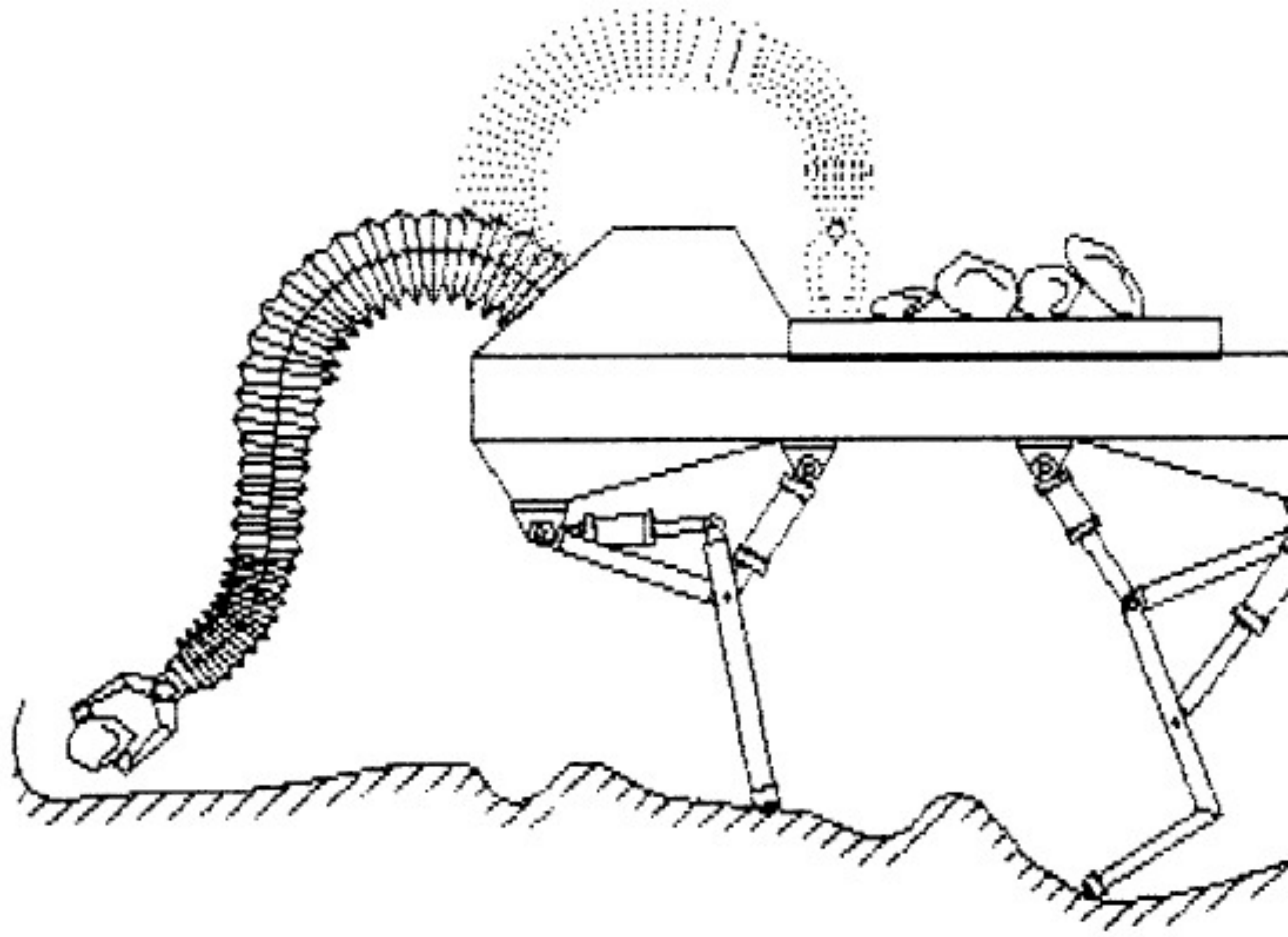
Began by studying the biomechanics of Snakes

Other Notable Work In The ‘80s



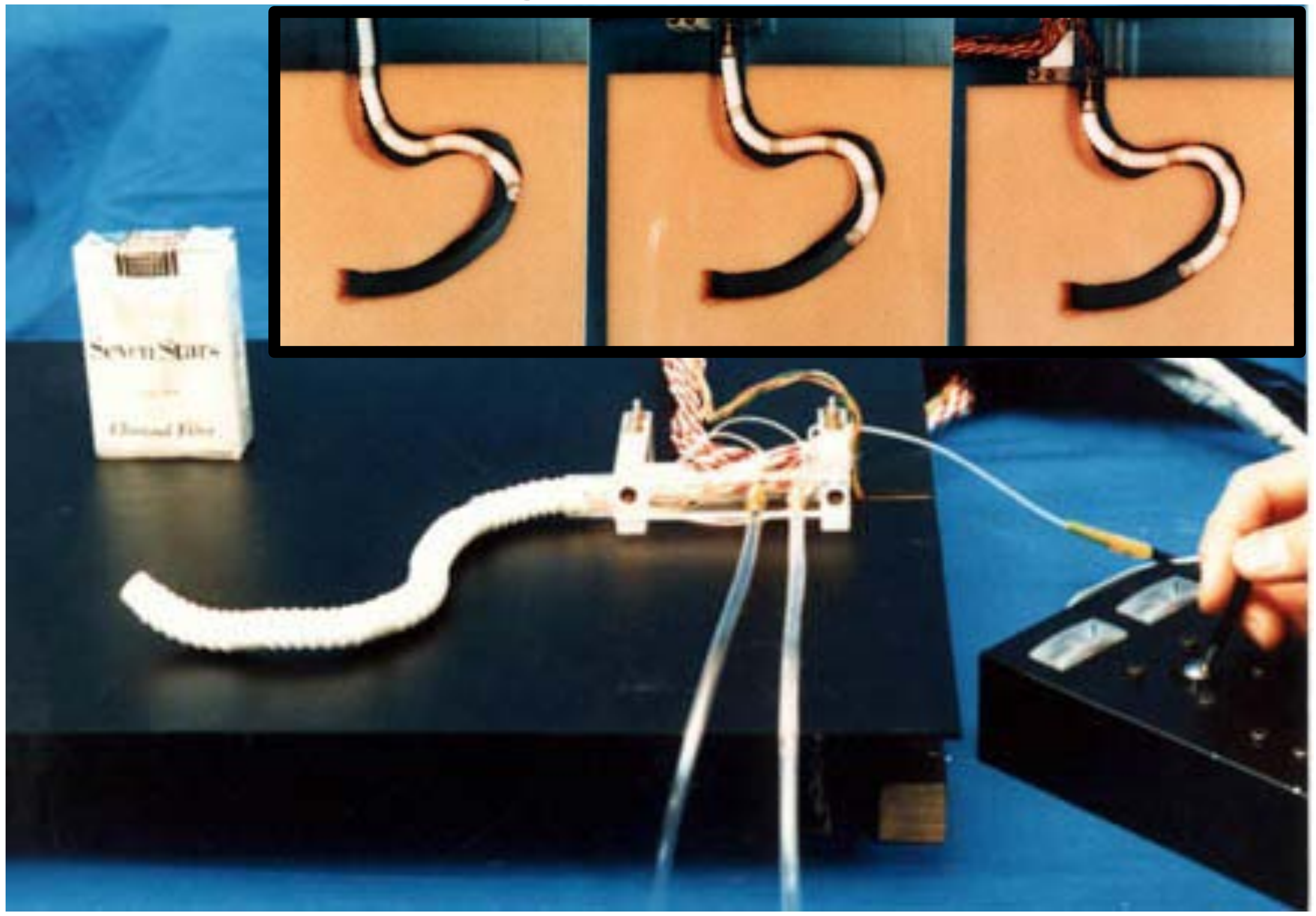
J.F. Wilson, U. Mahajan, “The Mechanics and Positioning of Highly Flexible Manipulator Limbs,” Journal of Mechanisms, Transmissions, and Automation in Design. 1989.

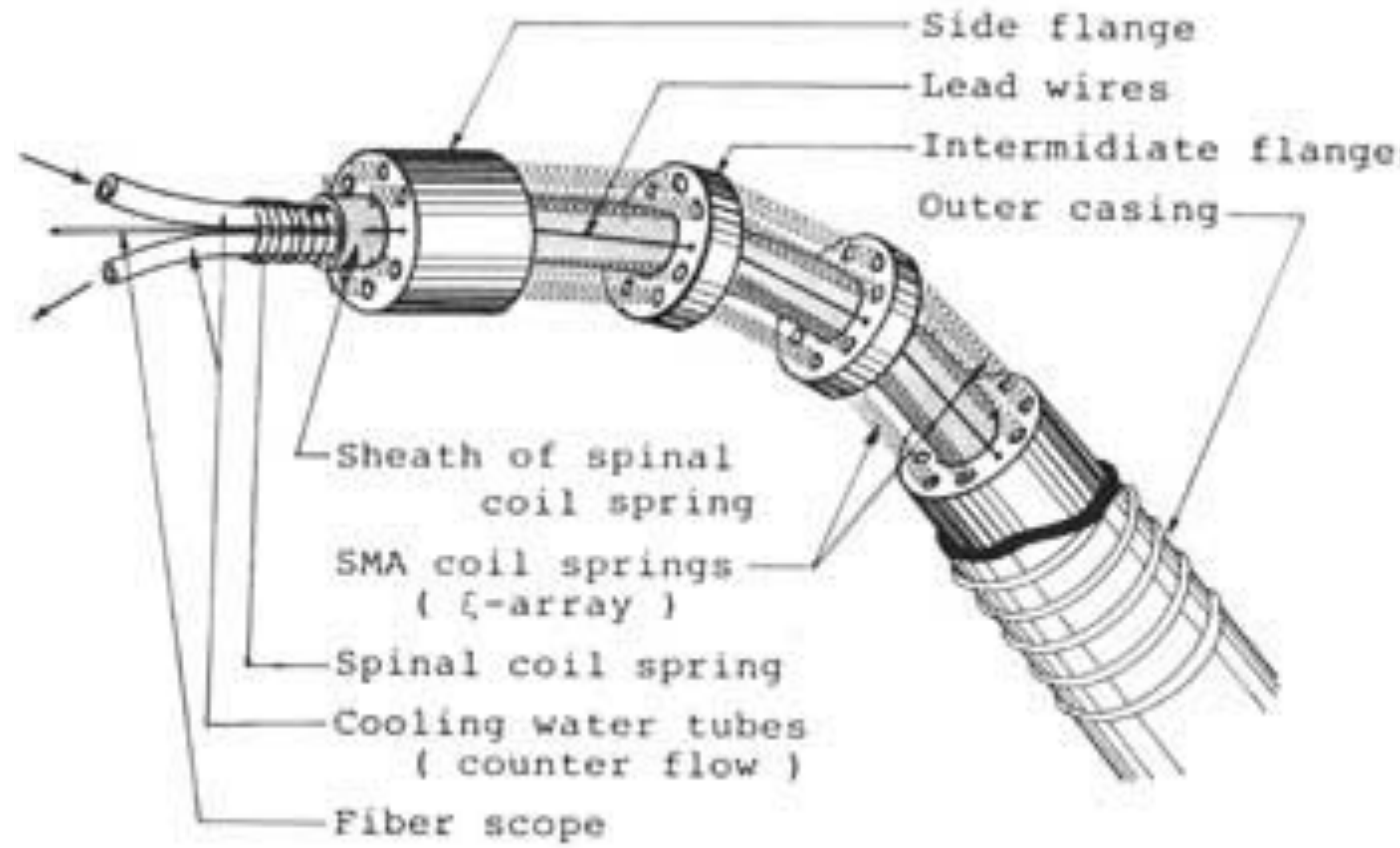




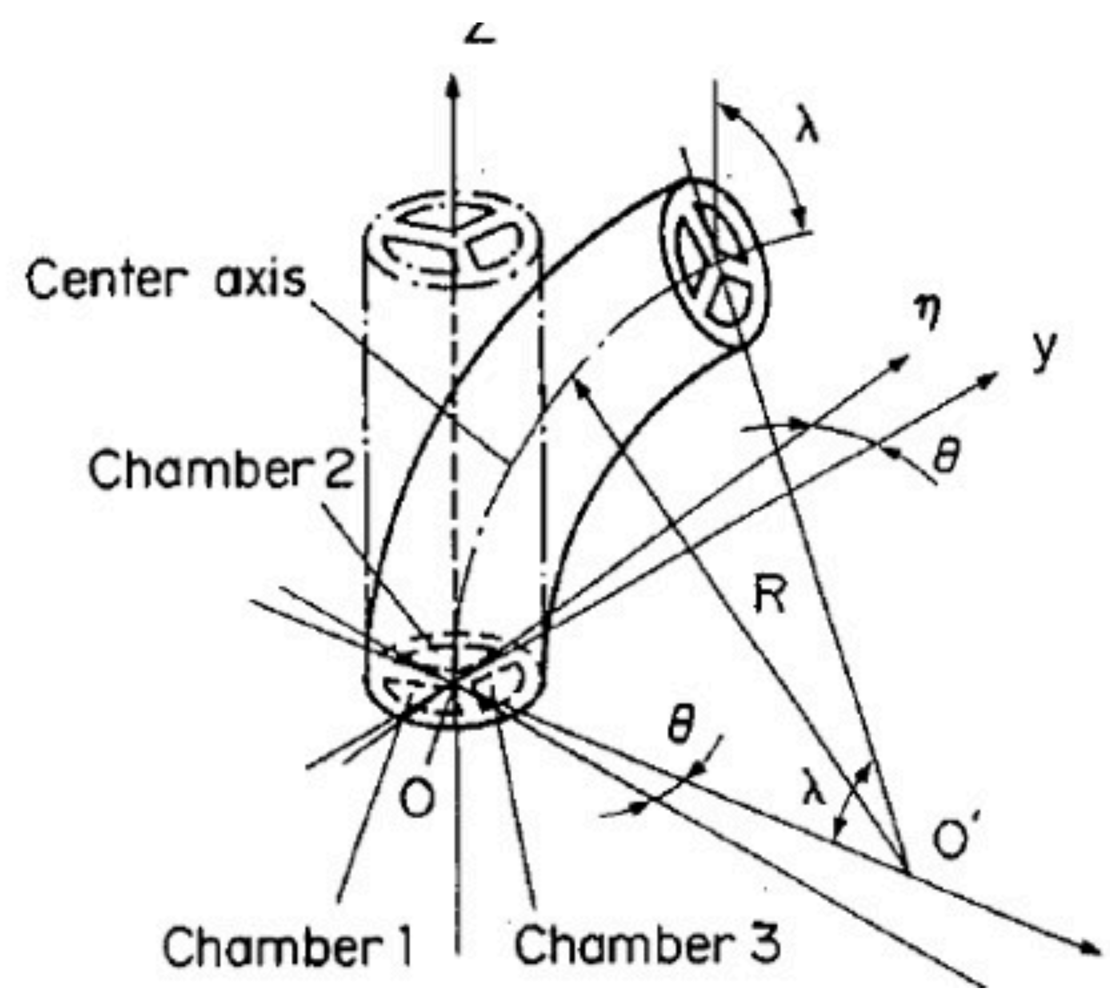
A. Morecki, K. Jaworek, W. Pogorzelski, T. Zielinska, J. Fraczek, G. Malczyk. “Robotics System—Elephant Trunk Type Elastic Manipulator Combined with a Quadruped Walking Machine.” Robotics and Factories of the Future 1987.

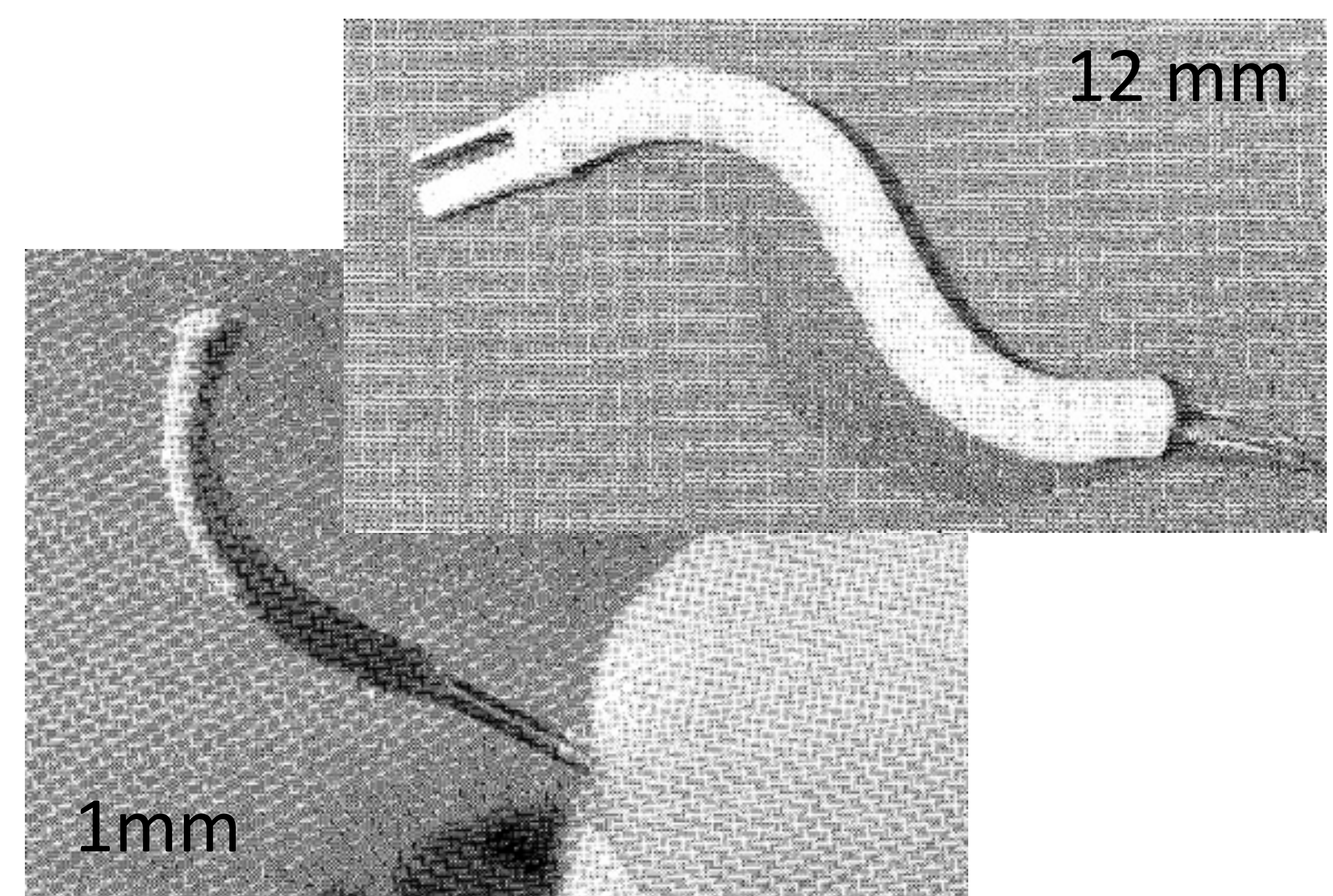
Early Medical Continuum Robots





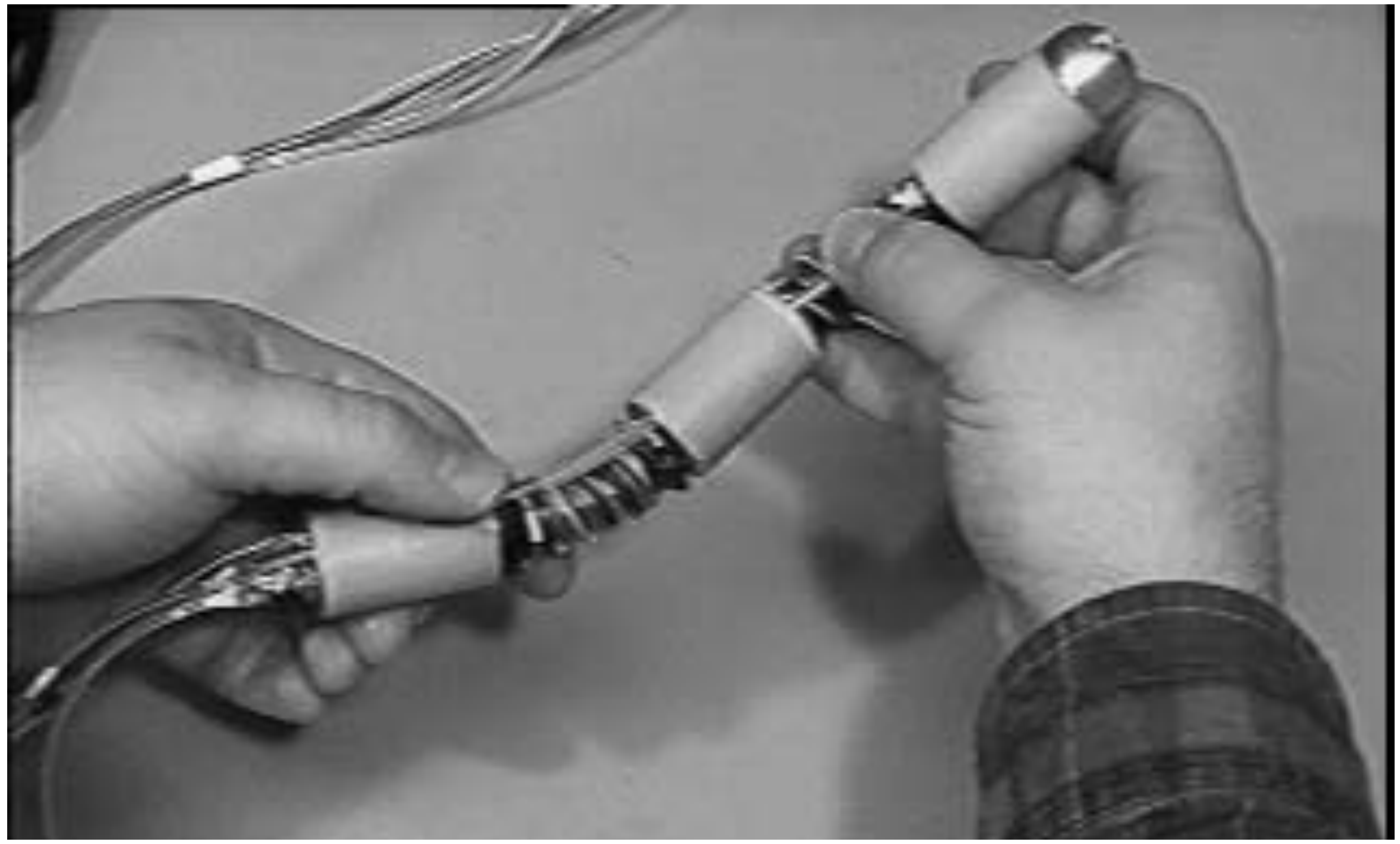
Hirose, Ikuta, and Tuskamoto, "Development of a Shape Memory Alloy Actuator", Advanced Robotics, 4(1), 3-27, 1989.

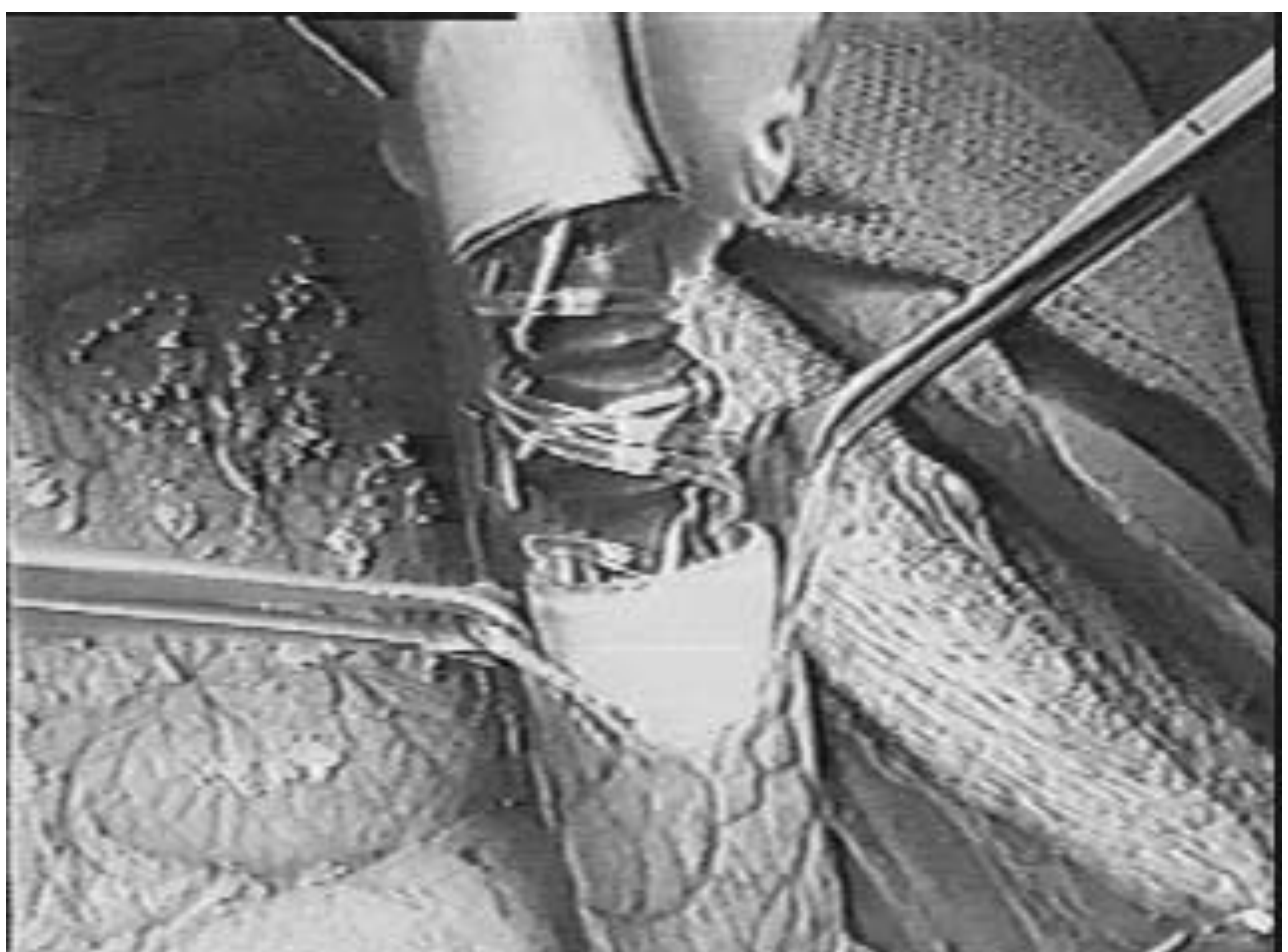


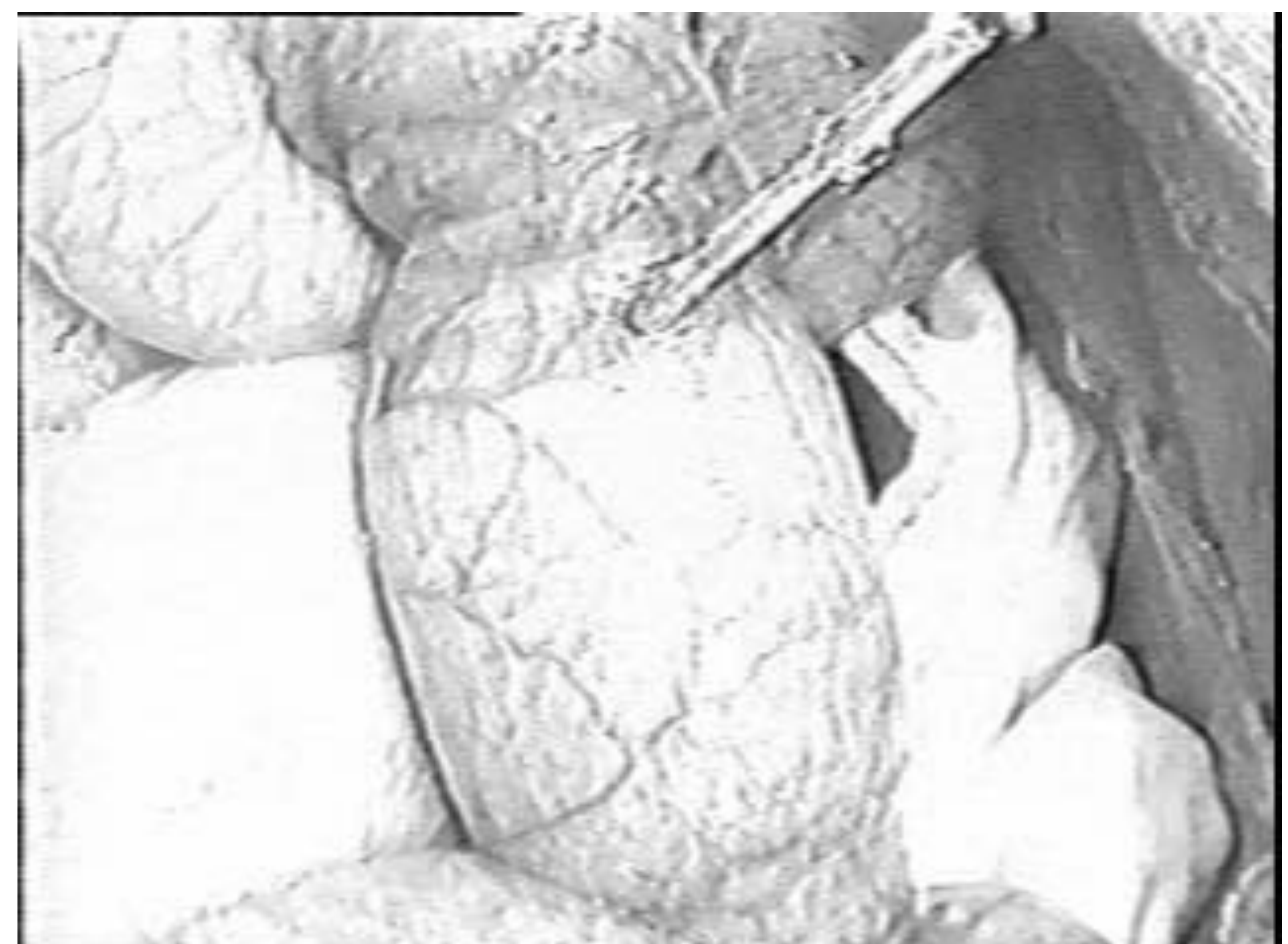


Suzumori, Ikura, and Tanaka "Development of flexible microactuator and its applications to robotic mechanisms" ICRA 1991.

Pneumatic Colon Robot: 1995







Grundfest, Burdick, and Slatkin, “The development of a robotic endoscope,” ICRA 1995.

Design/Modeling Chronology

Late '60s: Scheinman & Leifer	• Orm
Anderson & Horn	• Tensor Arm
Late '70s-today: Hirose, et al.	• First true continuum robots – many novel designs
Early '90s: Chirikjian	• Modeled Hyperredundant Robots as a Continuum • Modal approach to Inverse Kinematics
1995: Ivanescu	• Mechanics-based model of an electro-rheologtcal-fluid-actuated robot tentacle
2000's: Walker et al.	• Many contributions to design and modeling of non-medical continuum robots (tendon-driven and pneumatic)
2002: Loser & Taylor	• Steerable needle using concentric elastic tubes
2004: Simaan & Taylor	• Multi-backbone continuum robot
2004: Webster, Cowan, Chirikjian, Okamura	• Bevel-steered needles
2006: Webster, et al. Dupont, et al.	• Concentric-tube continuum robots
2008: Camarillio & Salisbury	• Hansen Catheter
Recent Years:	• A proliferation of innovative medical continuum robot designs - several interesting designs on subsequent slides

NOTE: Here ends chronology stuff. Don't infer any "firsts" or "bests" from later references in this talk.

A Recent Design Taxonomy

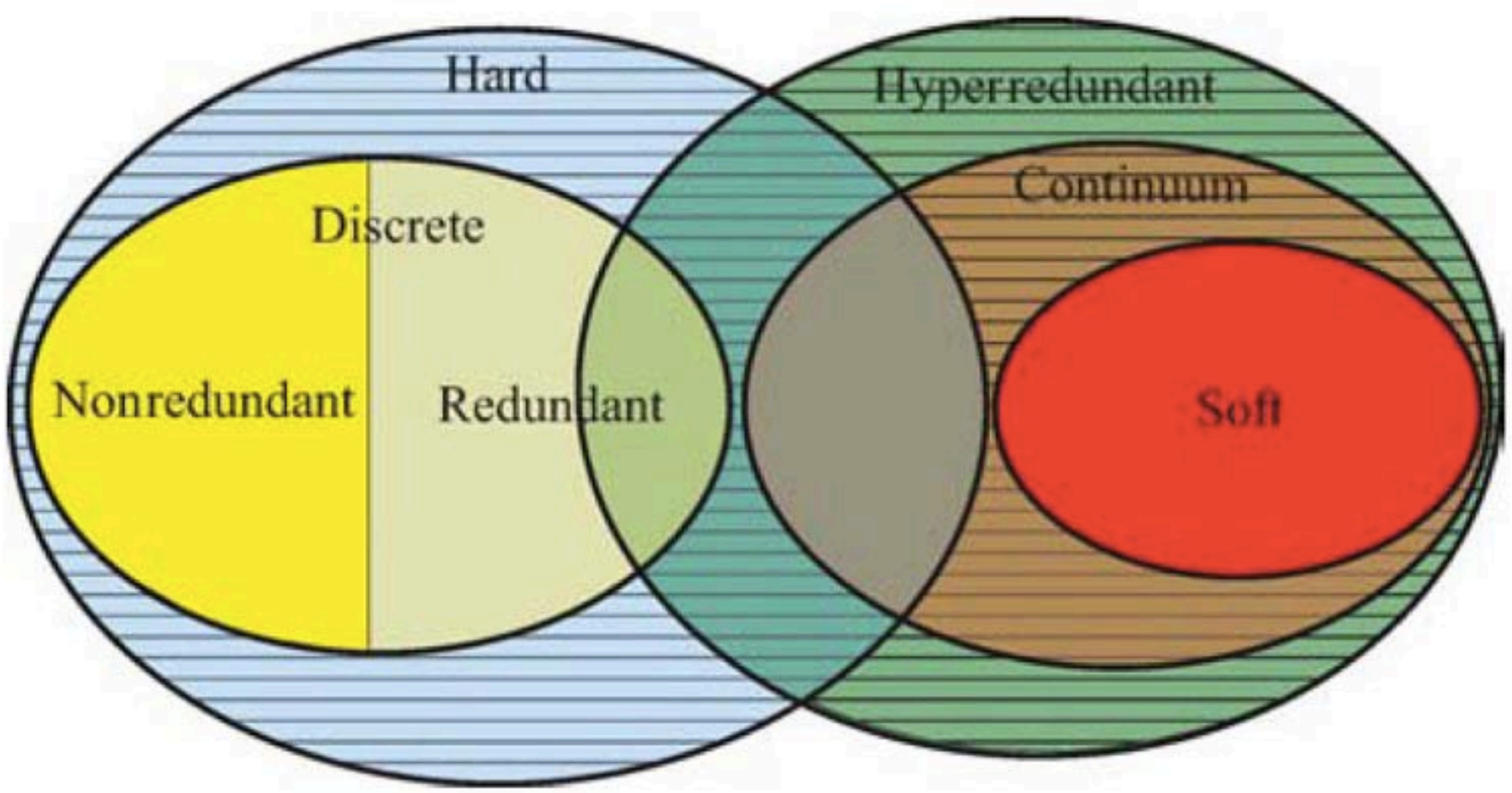
Classification criteria							
Continuous/ discrete	Extensible	Number of sections	Actuators/ section	DOF/ section	Actuator spacing	Actuation	Multi-section coupling**
D		4	4	2	90°	Tendon	Co-radial
D		5	3	2	120°	Tendon	Distributed
D		4	4	2	90°	Tendon/spring	Co-radial
C		3	2	2	90°	Tendon/spring	Co-radial
D		3	3	2	120°	Tendon/spring	Co-radial
C		1	1	1	180°	Tendon/rod	N/A
C		2	4	2	90°	Tendon/rod	Co-radial
D		1	1	2	180°	Tendon/rods	N/A
C	○	2	2	3	90°	Tendon/sleeve	Distributed
C	○	1	3	3	120°	Pneumatic	N/A
C	○	3	3	3	120°	Pneumatic	Individual
C	○	6	3	3	120°	Pneumatic	Individual
C	○	2	3	3	120°	Tendon/pneumatic	Co-radial
C	○	2	3	3	120°	Tendon/pneumatic	Distributed
C	○	2	3	2	120°	Tendon/pneumatic	Distributed
C	○	3	3	2	120°	Hydraulic	Individual
C		3	3	2	120°	Multibackbone	Co-located
C	○	$2n$	1	2	–	n curved tubes	*
C	○	∞	0	3	–	Tip/tissue	Individual

R. J. Webster III and B. A. Jones. Design and Kinematic Modeling of Constant Curvature Continuum Robots: A Review. International Journal of Robotics Research, 29(13), 1661-1683, 2010.

Another Categorization

Table 1. Characteristics of different types of hard (first three columns) and soft robots.

	Rigid	Discrete hyperredundant	Hard continuum	Soft
Properties				
df	Few	Large	Infinite	Infinite
Actuators	Few, discrete	Many, discrete	Continuous	Continuous
Material strain	None	None	Small	Large
Materials	Metals, plastics	Metals, plastics	Shape memory alloy	Rubber, electroactive polymer
Capabilities				
Accuracy	Very high	High	High	Low
Load capacity	High	Lower	Lower	Lowest
Safety	Dangerous	Dangerous	Dangerous	Safe
Dexterity	Low	High	High	High
Working environment	Structured only	Structured and unstructured	Structured and unstructured	Structured and unstructured
Manipulable objects	Fixed sized	Variable size	Variable size	Variablesize
Conformability to obstacles	None	Good	Fair	Highest
Design				
Controllability	Easy	Medium	Difficult	Difficult
Path planning	Easy	Harder	Difficult	Difficult
Position Sensing	Easy	Harder	Difficult	Difficult
Inspiration	Mammalian limbs	Snakes, fish		Muscular hydrostats



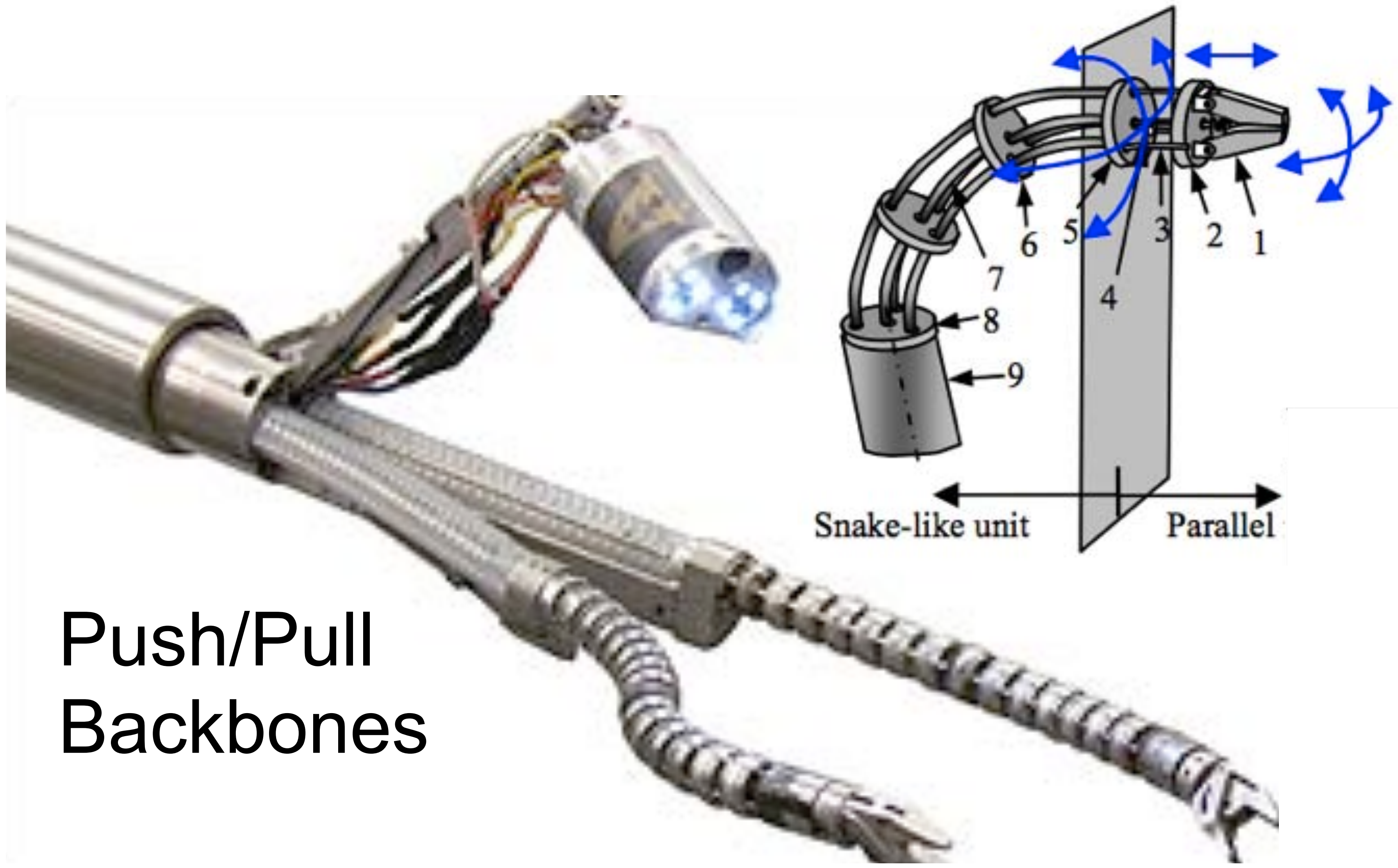
Trivedi, Rahn, Kier, and Walker, "Soft robotics: Biological inspiration, state of the art, and future research," Applied Bion. and Biomech. 2008.

Some Examples

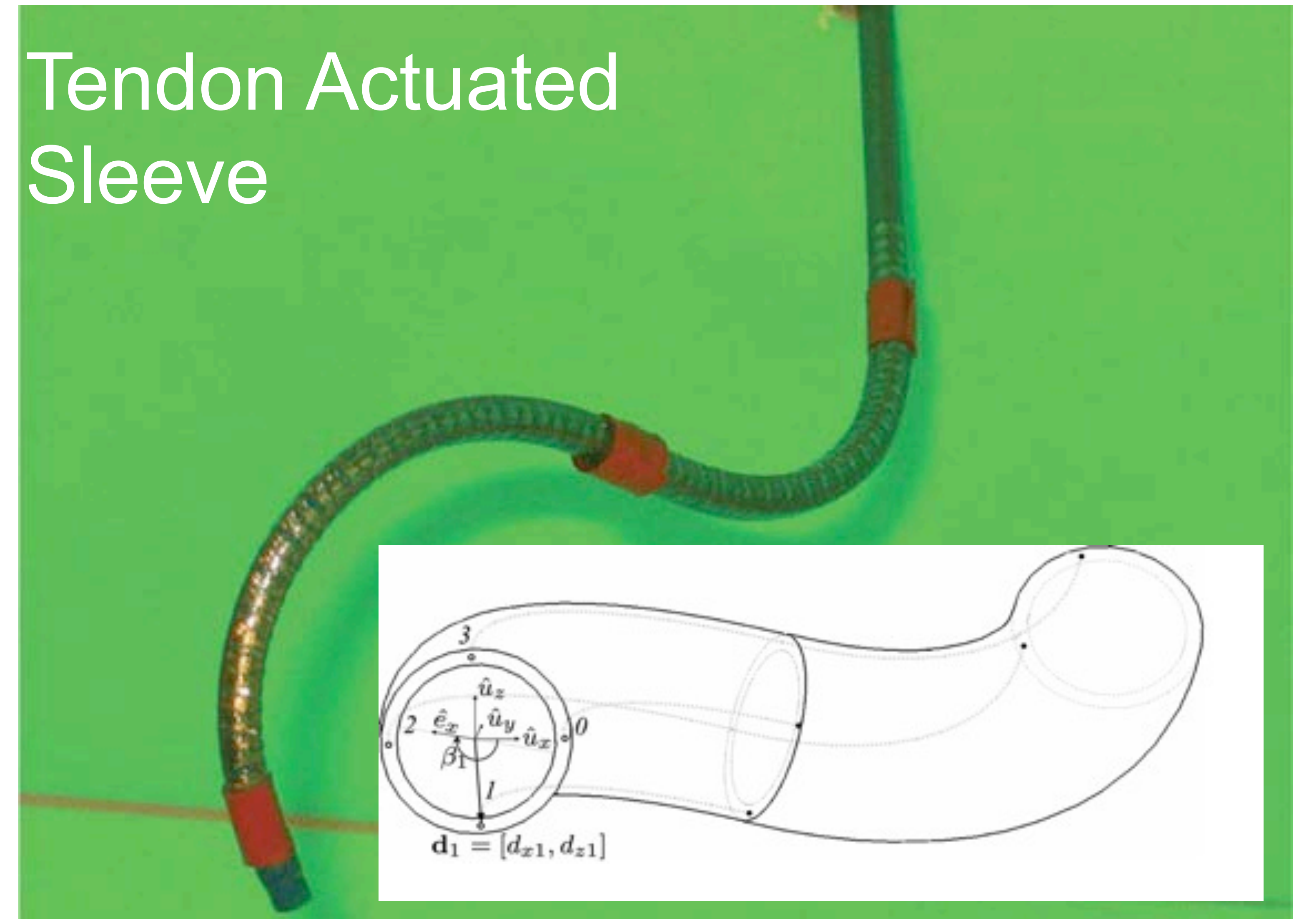
NOTE: The following is NOT comprehensive.

There are many cool designs out there not listed on the following slides

Continuum Robot Design: Some Examples



Simaan, et al. "Design and Integration of a Telerobotic System for Minimally Invasive Surgery of the Throat." IJRR 2009.

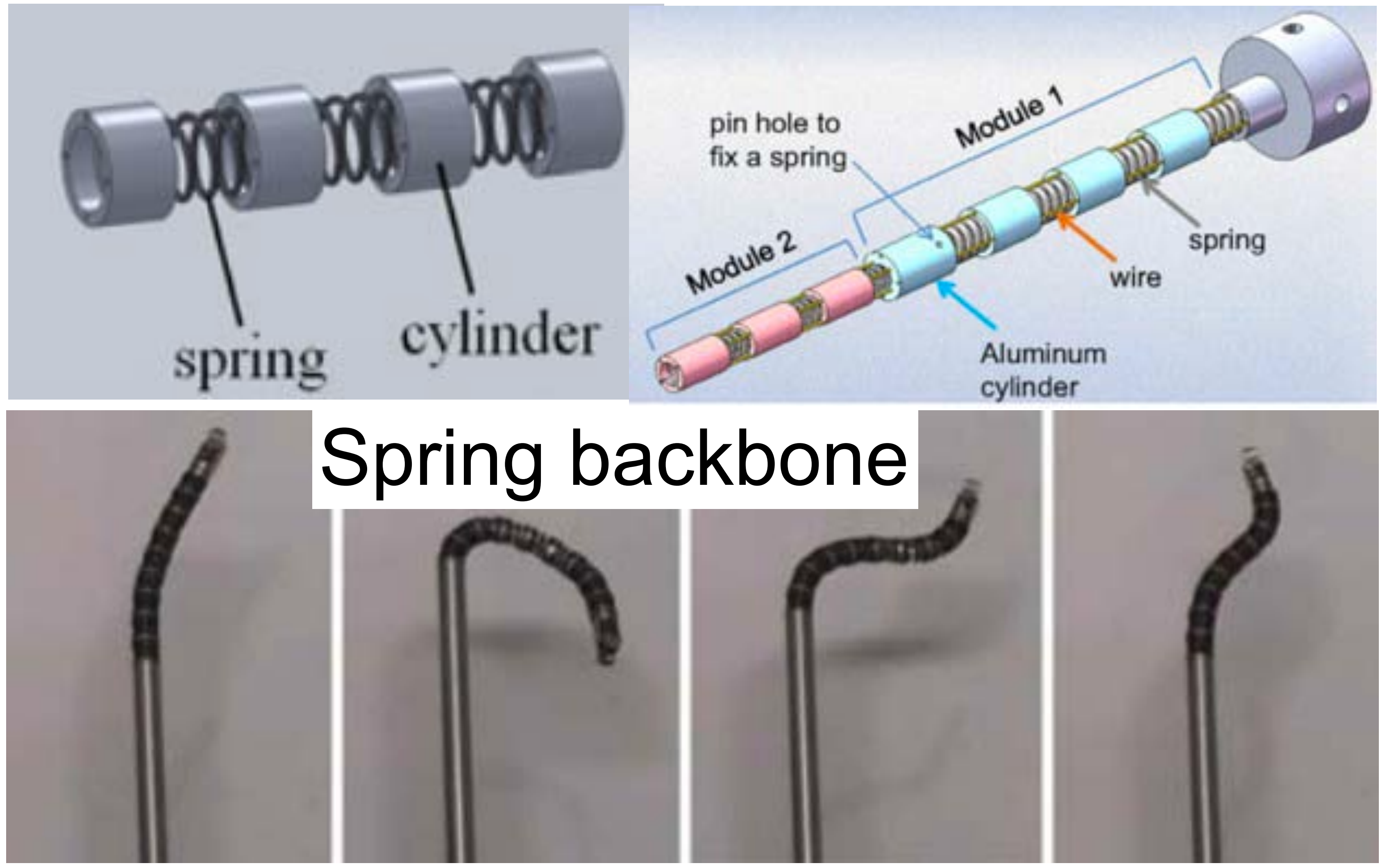


Camarillo, Milne, Carlson, Zinn, and Salisbury, "Mechanics modeling of tendon-driven continuum manipulators," TRO, 2008.

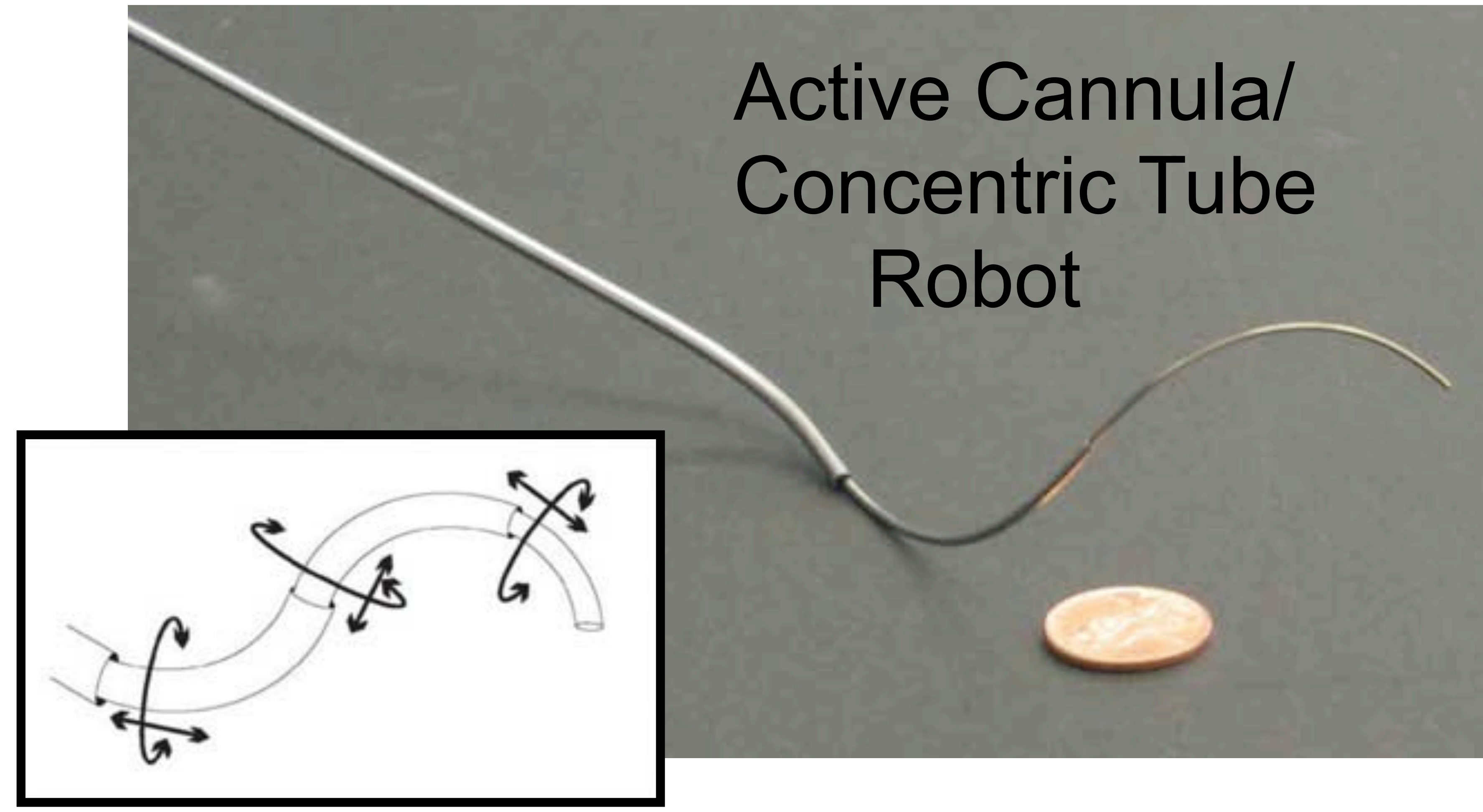
Gravagne, Rahn, and Walker, "Large deflection dynamics and control for planar continuum robots," TMECH 2003.

Ikuta, Ichikawa, Suzuki, Yajima, "Multi-degree of freedom hydraulic pressure driven safety active catheter," *ICRA 2006.*

Continuum Robot Design: Some Examples

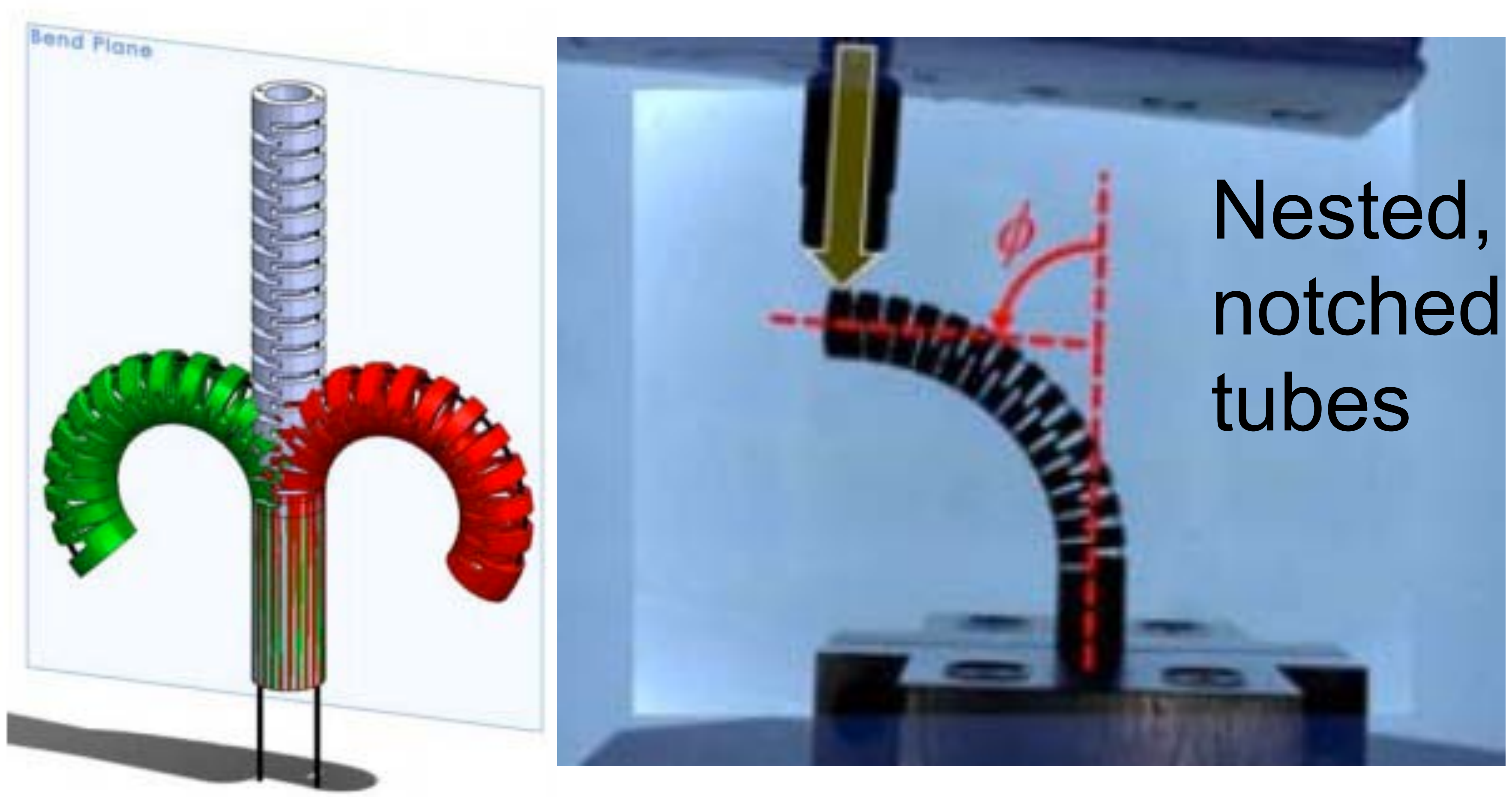


Choi, Yi, and Kim, "Design of a spring backbone micro endoscope," IROS 2007.

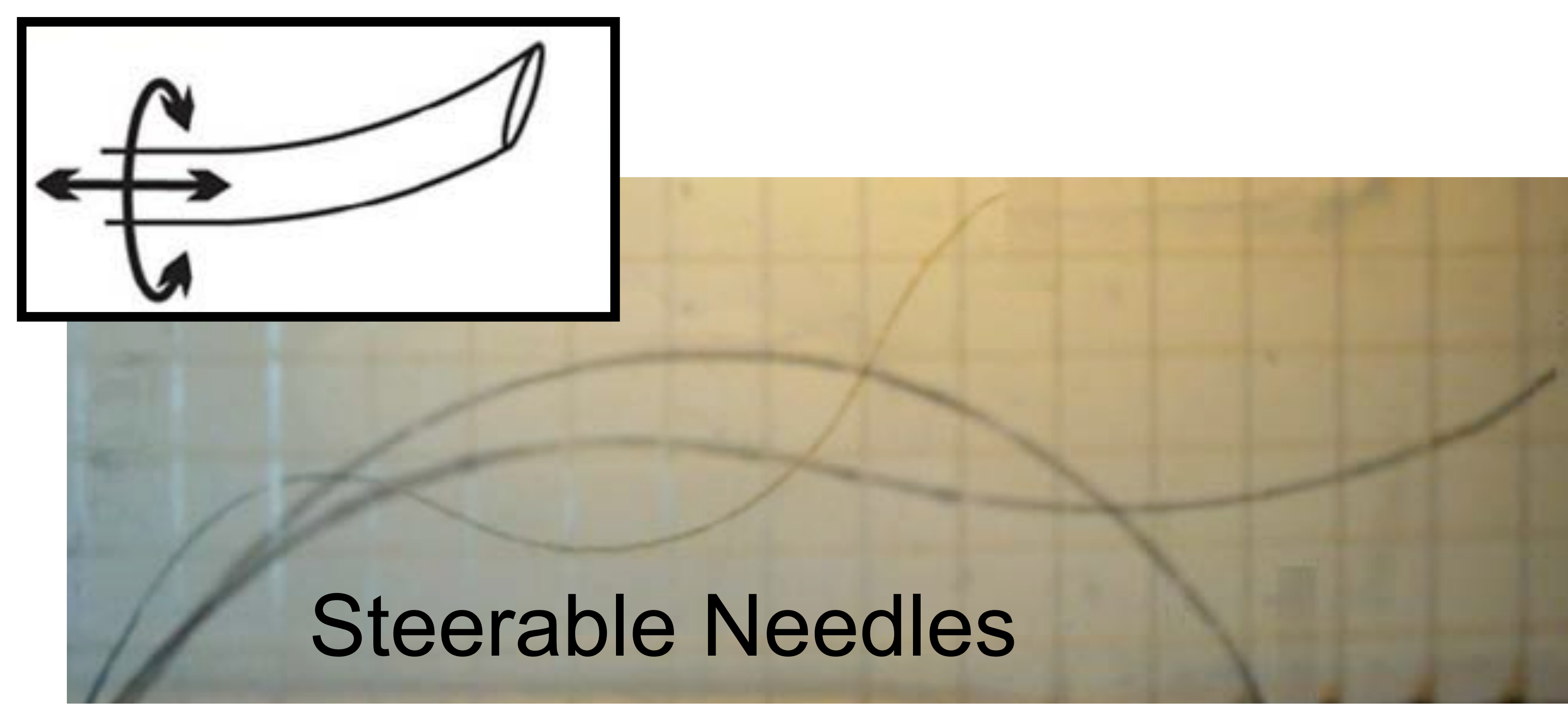


Webster, Romano, and Cowan. “Mechanics of Precurved-Tube Continuum Robots,” TRO, 2009.

Dupont, Lock, Itkowitz, and Butler, "Design and Control of Concentric-Tube Robots," TRO, 2010.

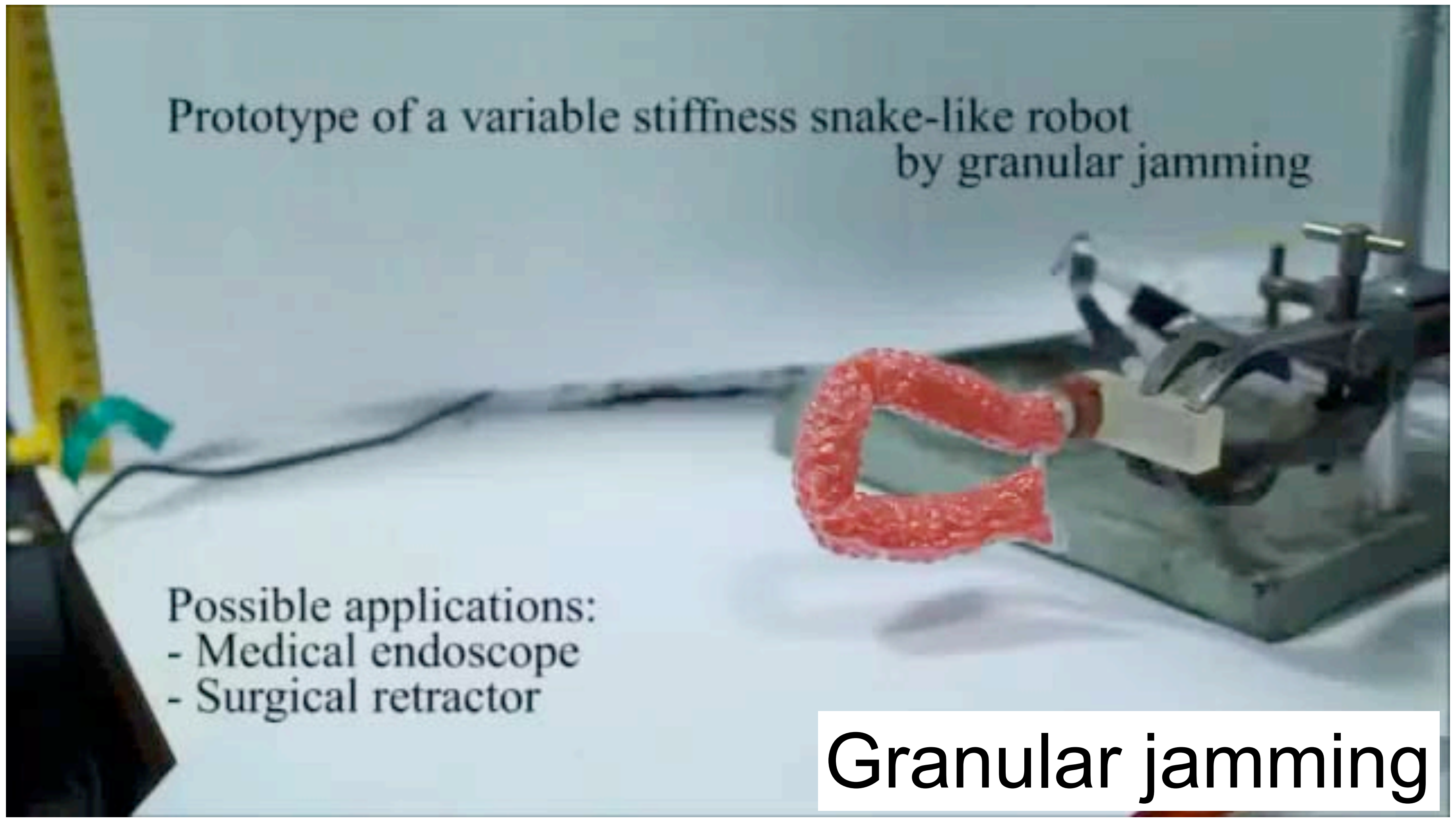


Kutzer, Segreti, Brown, Armand, Taylor, and Mears, "Design of a new cable-driven manipulator with a large open lumen," ICRA 2011.

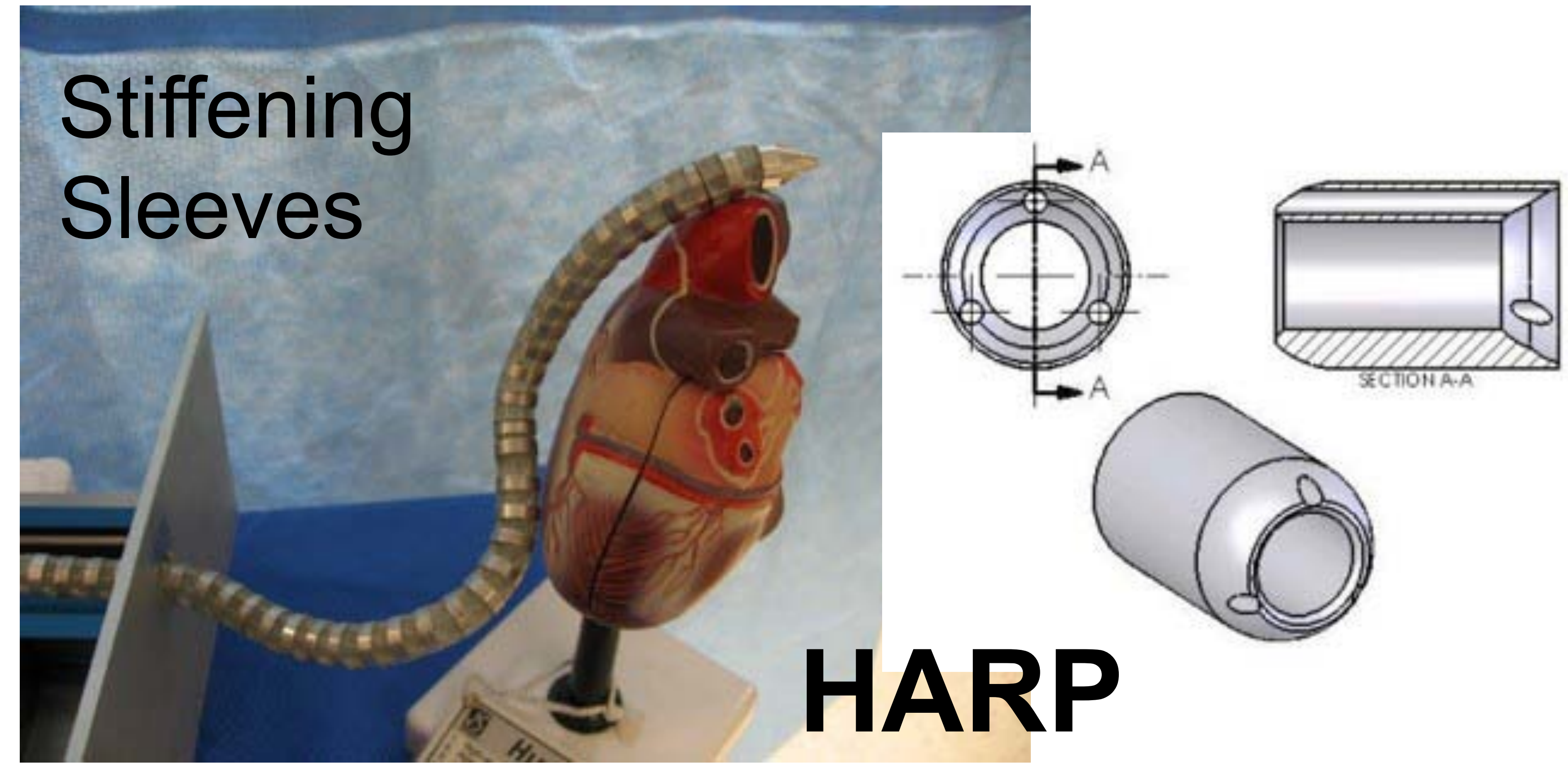


Webster, Kim, Cowan, Chirikjian, and Okamura. “Nonholonomic Modeling of Needle Steering,” IJRR, 2006.

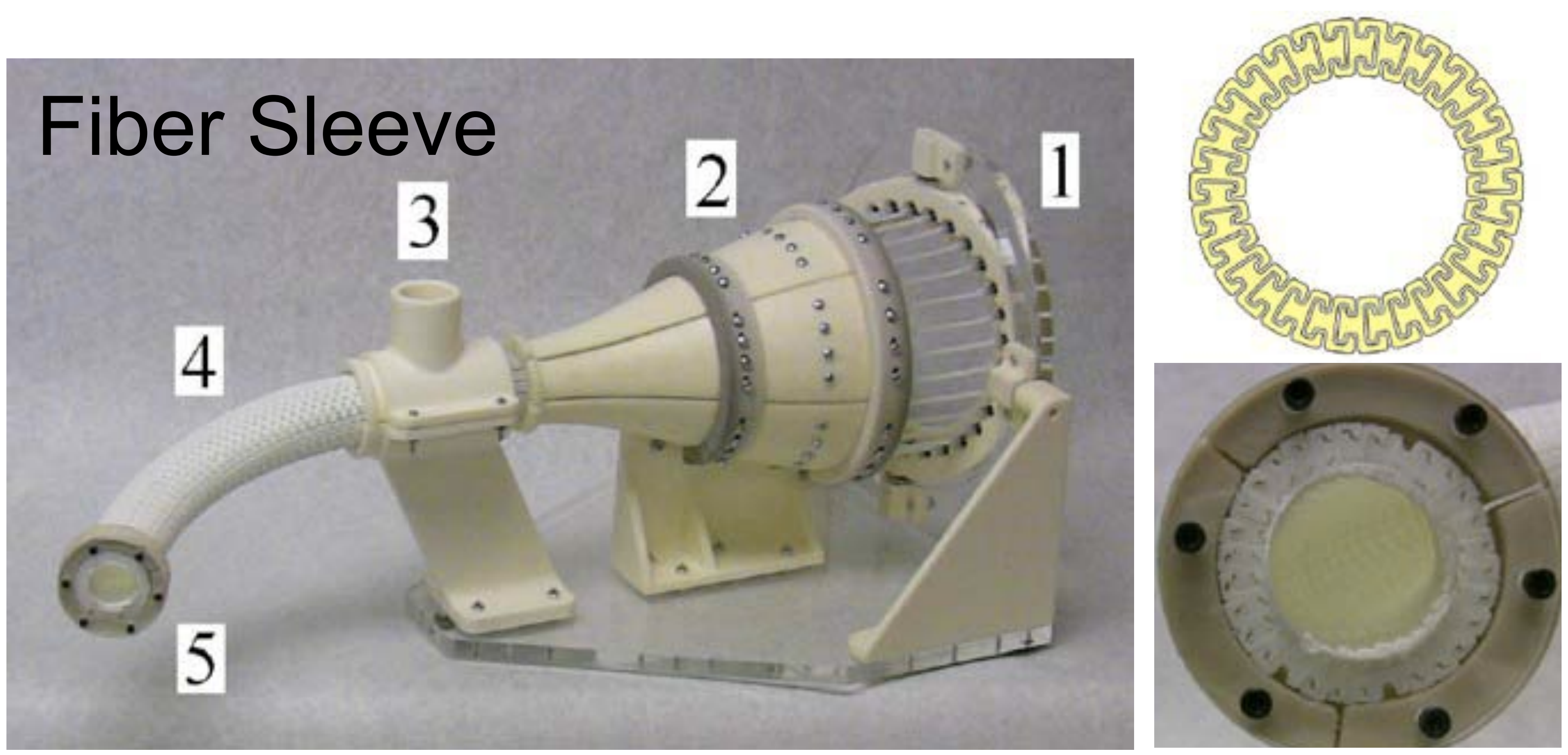
Continuum Robot Design: Some Examples



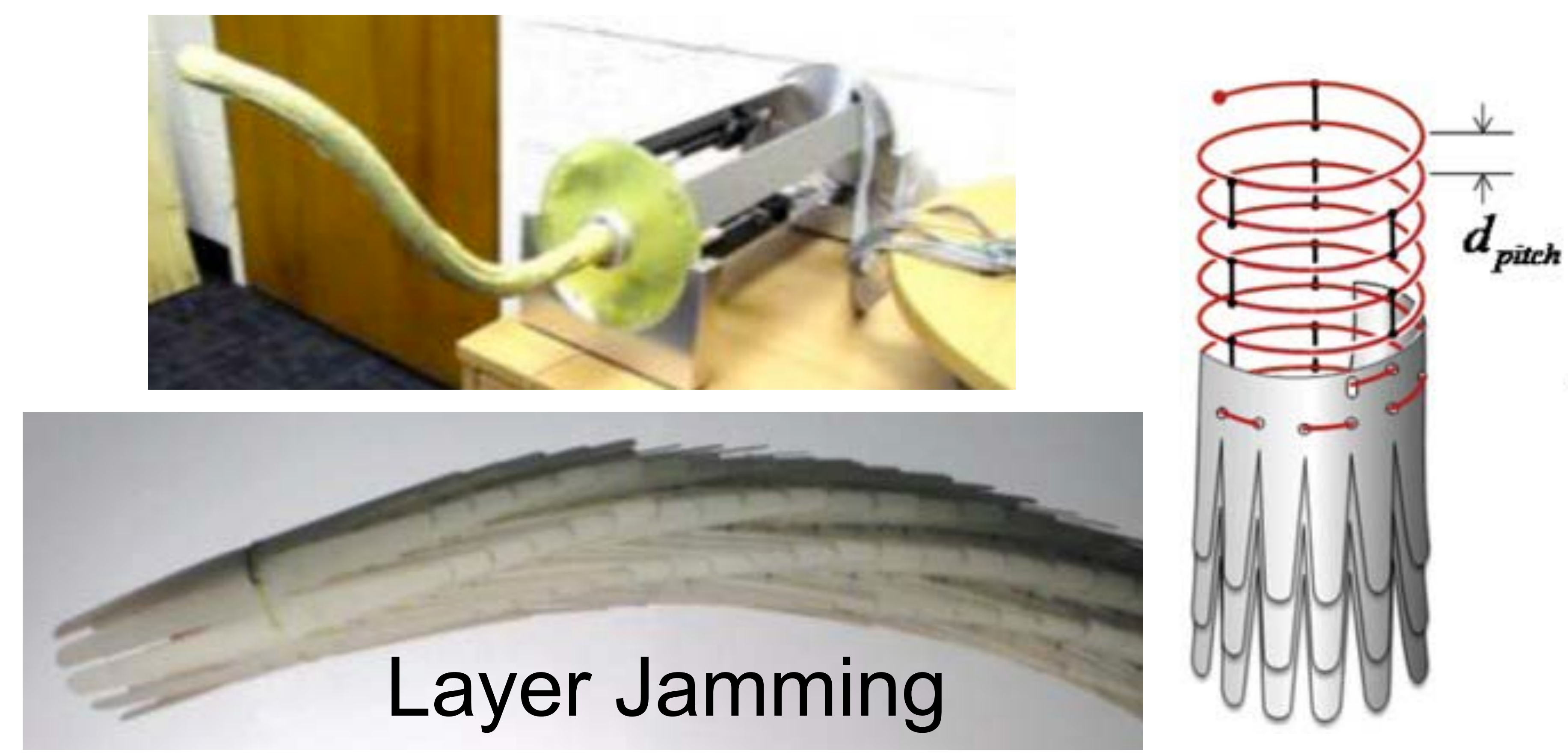
Wurdemann, Jiang, Nanayakkara, Seneviratne, Althoefer, "Variable Stiffness Controllable and Learnable Manipulator for MIS," ICRA 2012.



Degani, Choset, Wolf, and Zenati, "Highly articulated robotic probe for minimally invasive surgery," ICRA 2006.

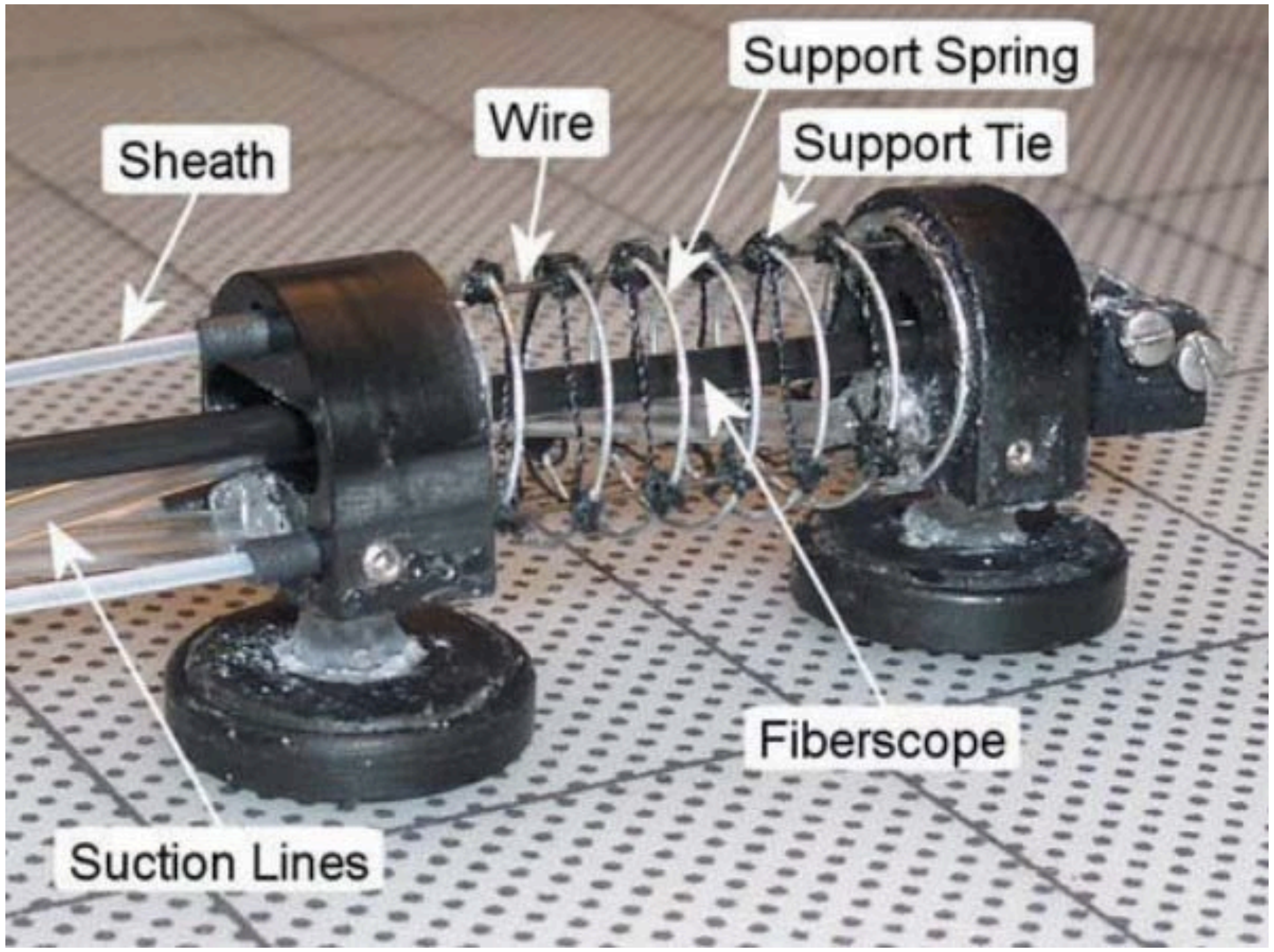


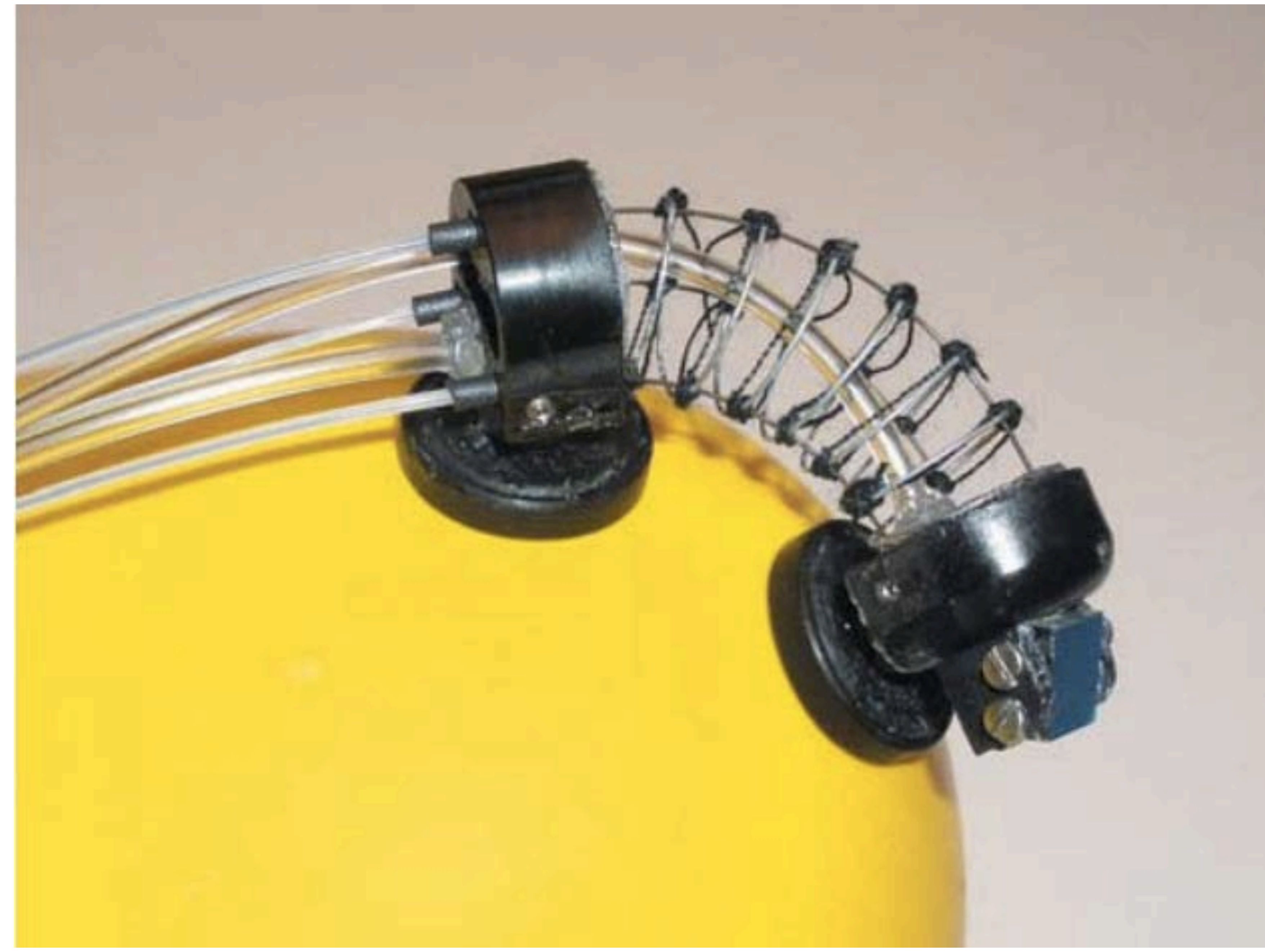
M.S. Moses, M. Kutzer, M. Hans, M. Armand. "A Continuum Manipulator Made of Interlocking Fibers." ICRA 2013.



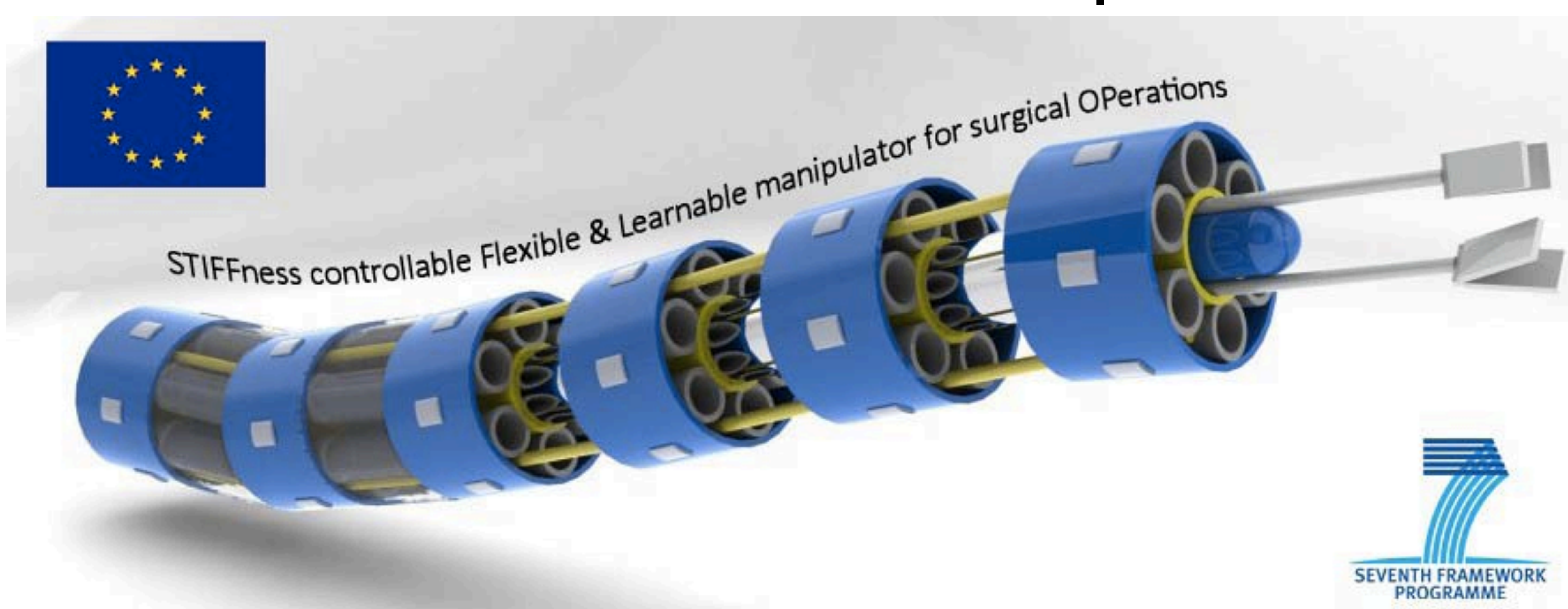
Y. Kim, S. Cheng, S. Kim, K. Iagnemma, "Design of a tubular snake-like manipulator with stiffening capability by layer jamming," IROS 2012.

Even Heartlander is a Continuum Robot!



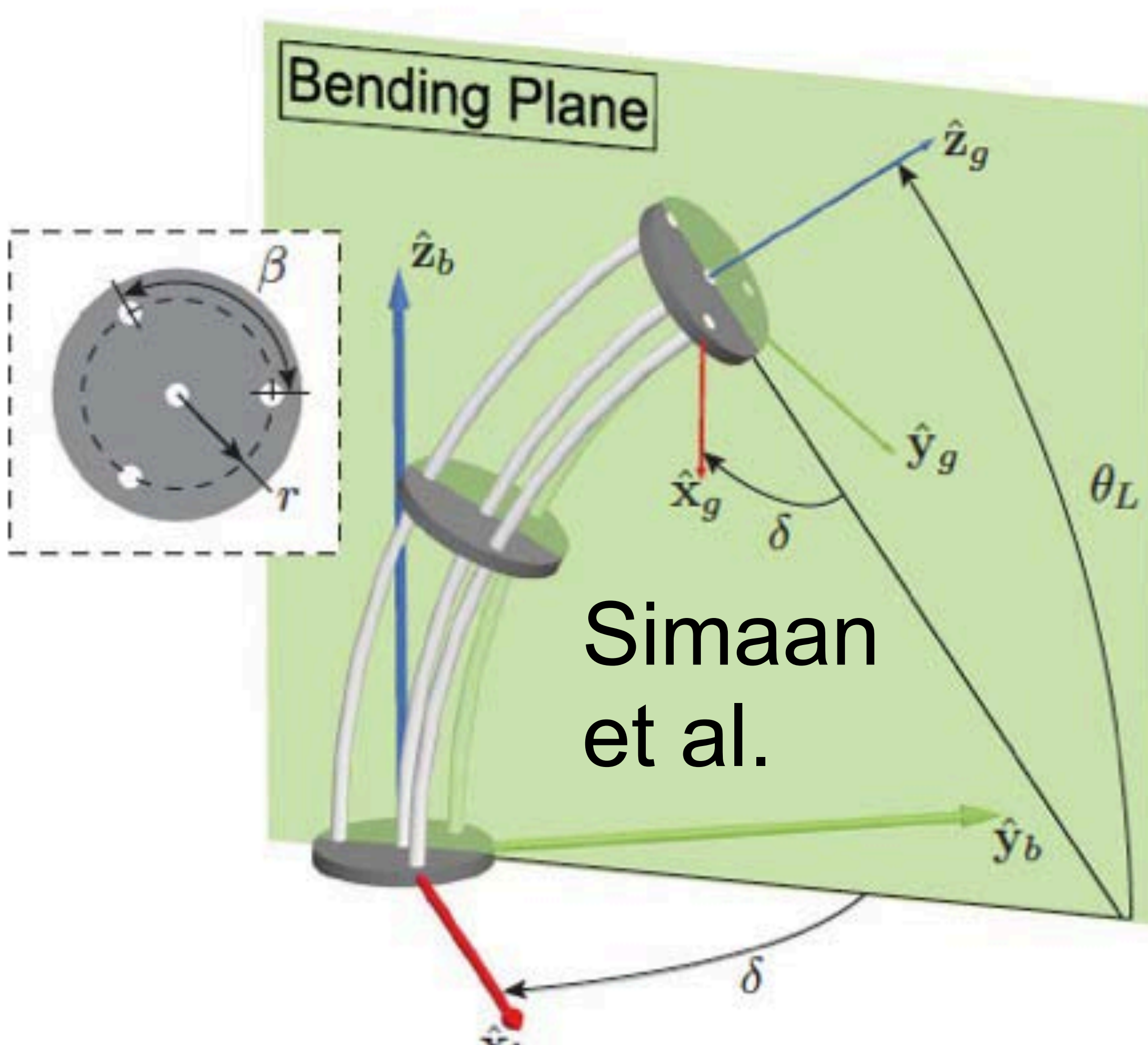


And of Course Stiff Flop is Too

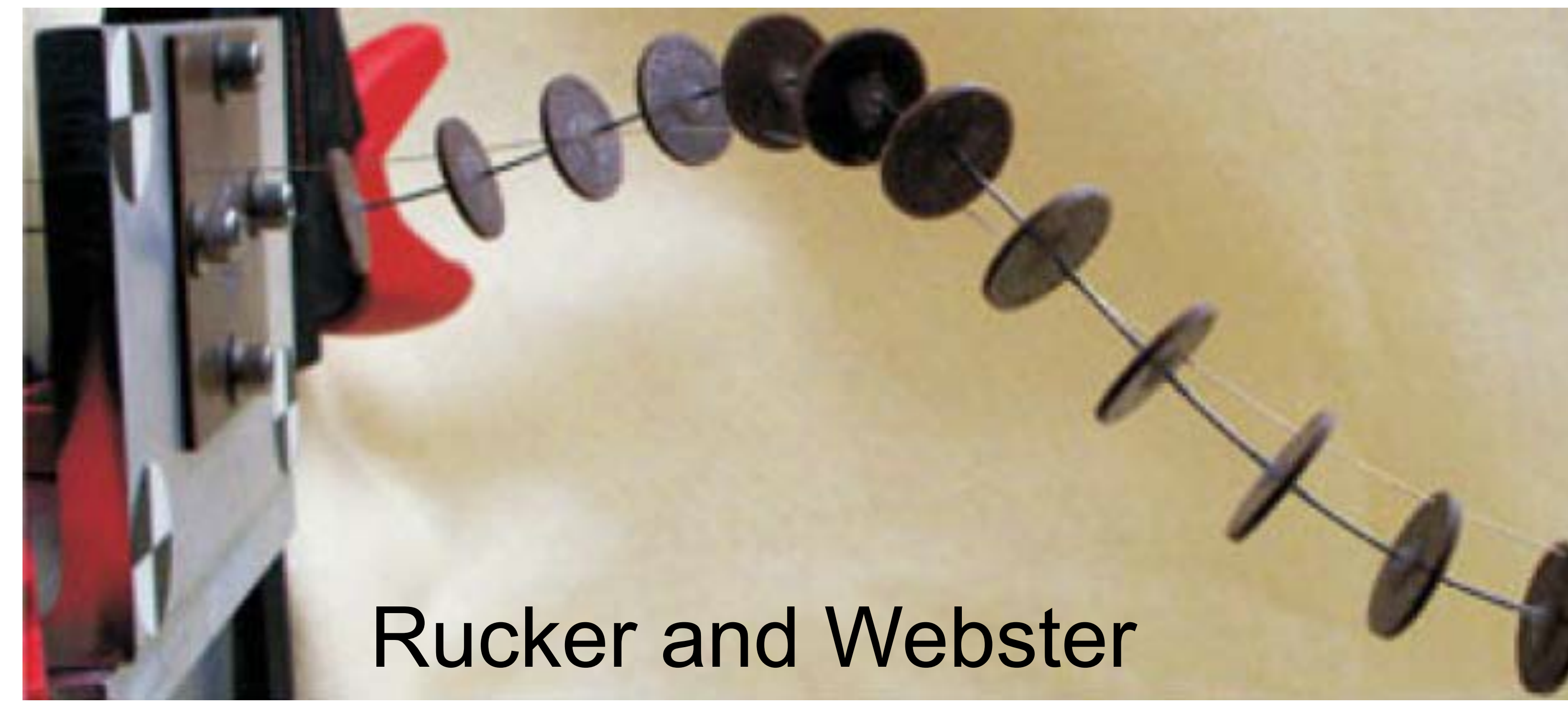


Modeling: The Big Question - Constant Curvature?

CONSTANT CURVATURE



VARIABLE CURVATURE

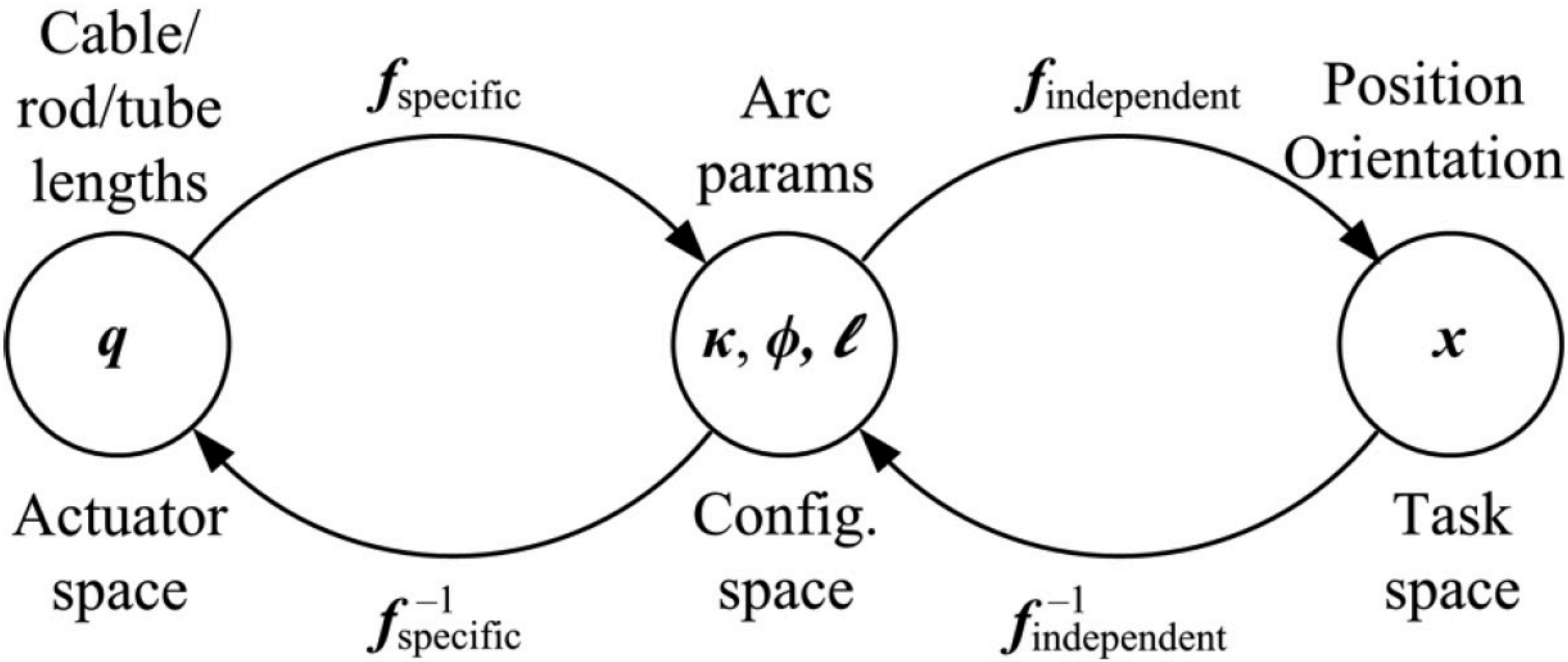


“Statics and Dynamics of Continuum Robots With General Tendon Routing and External Loading,” TRO 2011.

Tunay, "Spatial Continuum Models of Rods Undergoing Large Deformation and Inflation," TRO 2013.

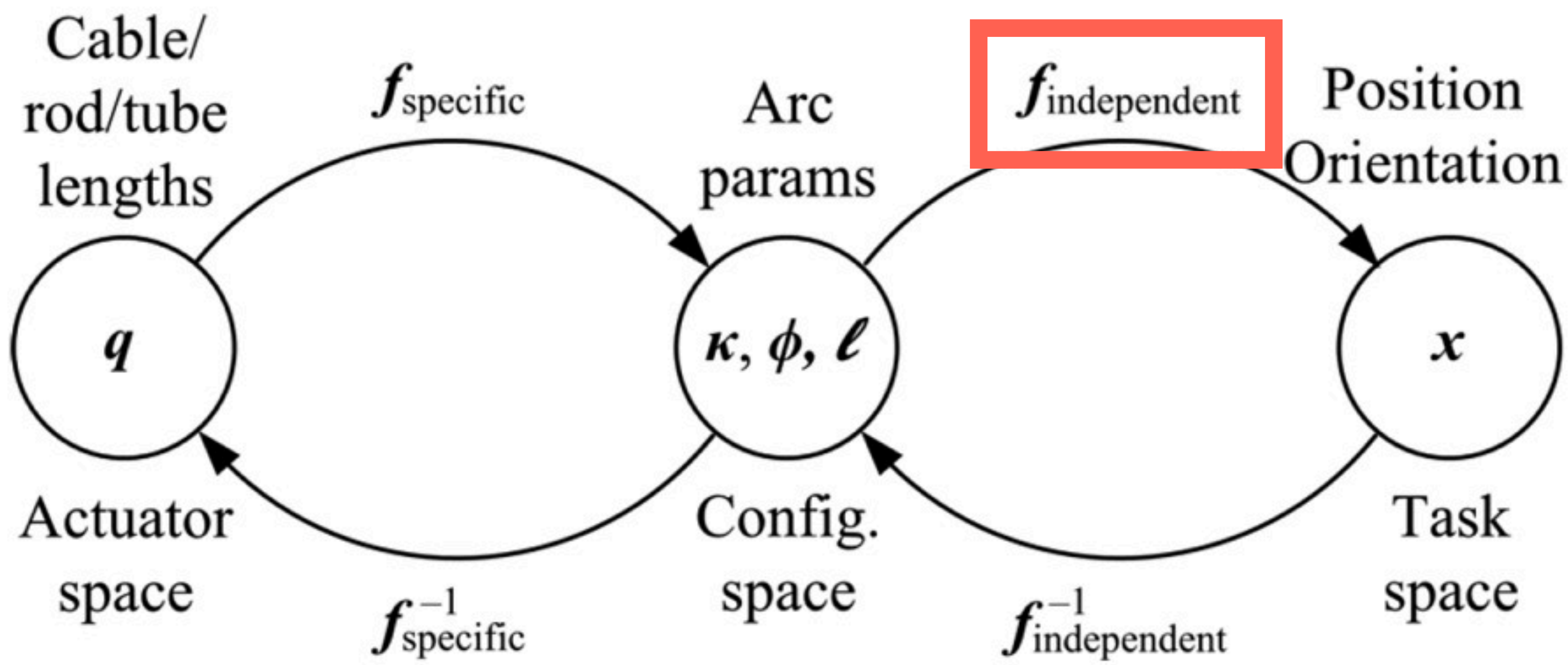
Stuart S. Antman. Nonlinear Problems of Elasticity. Springer Science, 2nd edition, 2005.

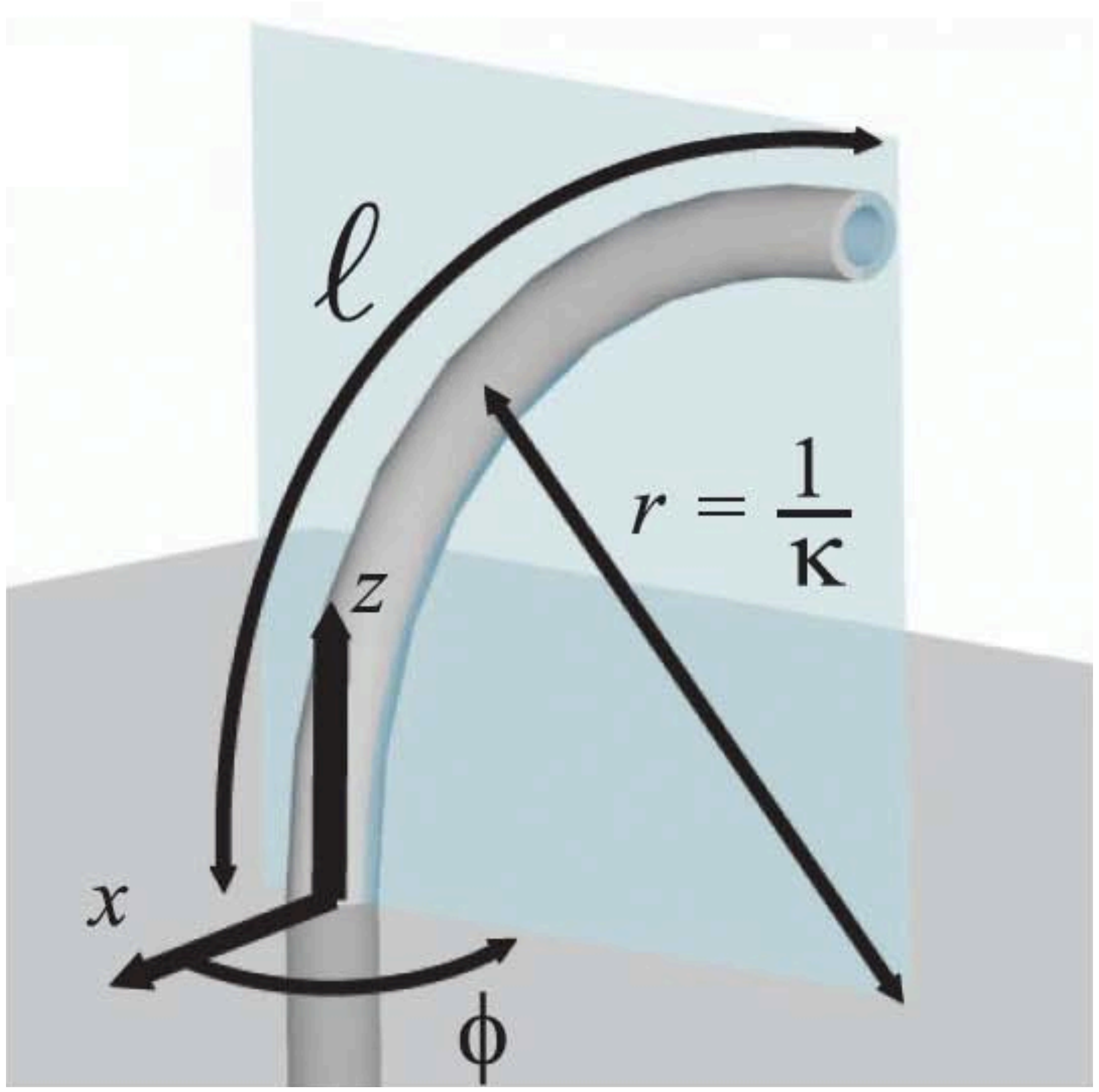
Constant Curvature Modeling

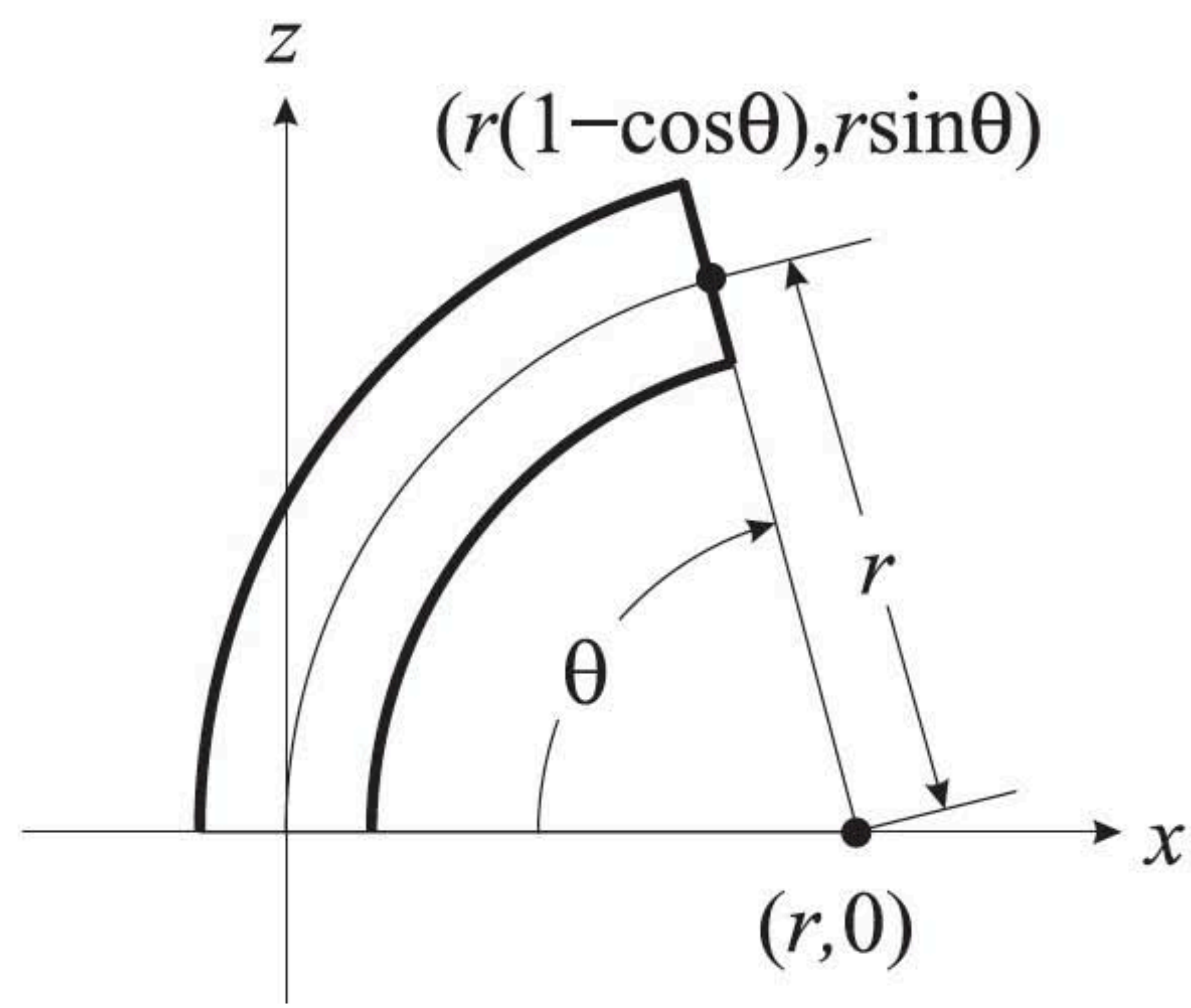


R. J. Webster III and B. A. Jones. Design and Kinematic Modeling of Constant Curvature Continuum Robots: A Review. International Journal of Robotics Research, 29(13), 1661-1683, 2010.

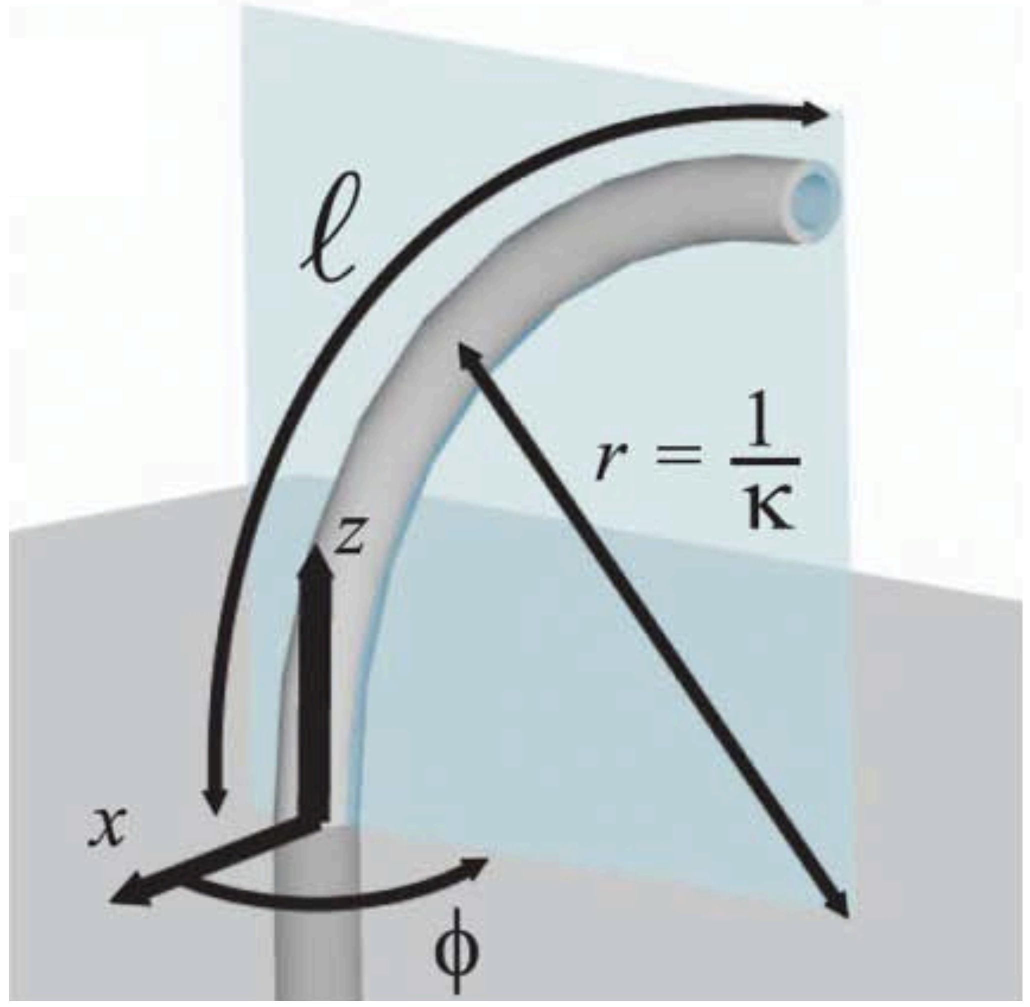
Constant Curvature Kinematics

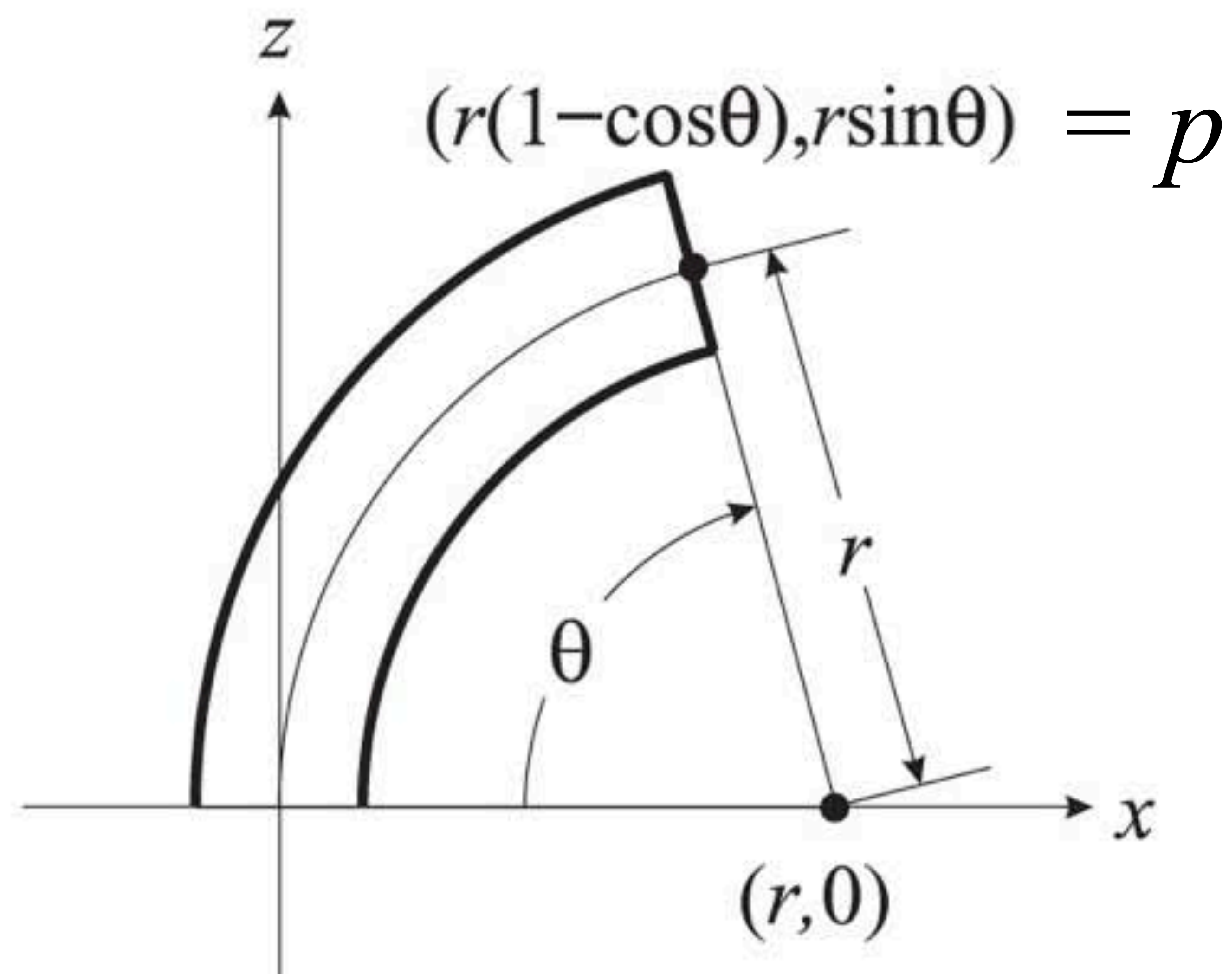






Constant Curvature Kinematics





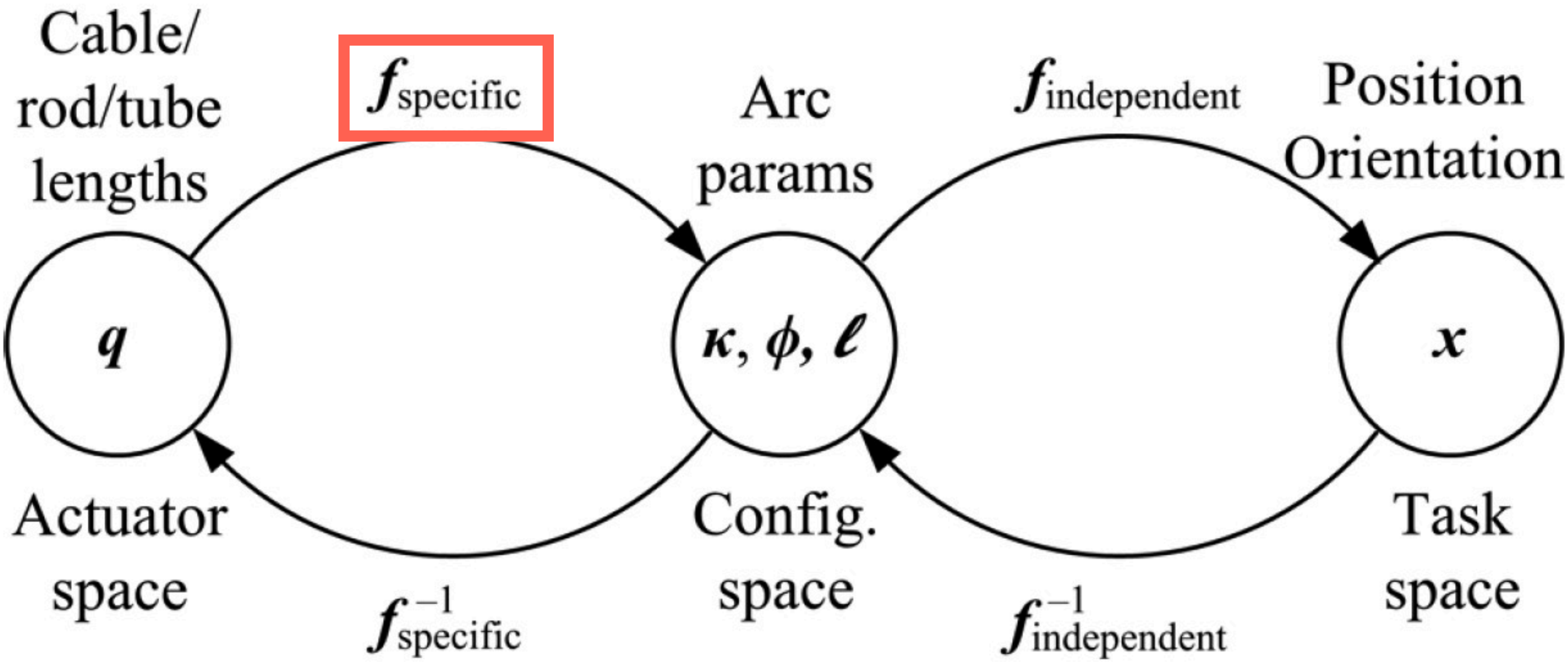
$$T = \underbrace{\begin{bmatrix} R_z(\phi) & 0 \\ 0 & 1 \end{bmatrix}}_{\text{Rotation}} \underbrace{\begin{bmatrix} R_y(\theta) & \boldsymbol{p} \\ 0 & 1 \end{bmatrix}}_{\text{Inplane transformation}}$$

Constant Curvature Kinematics

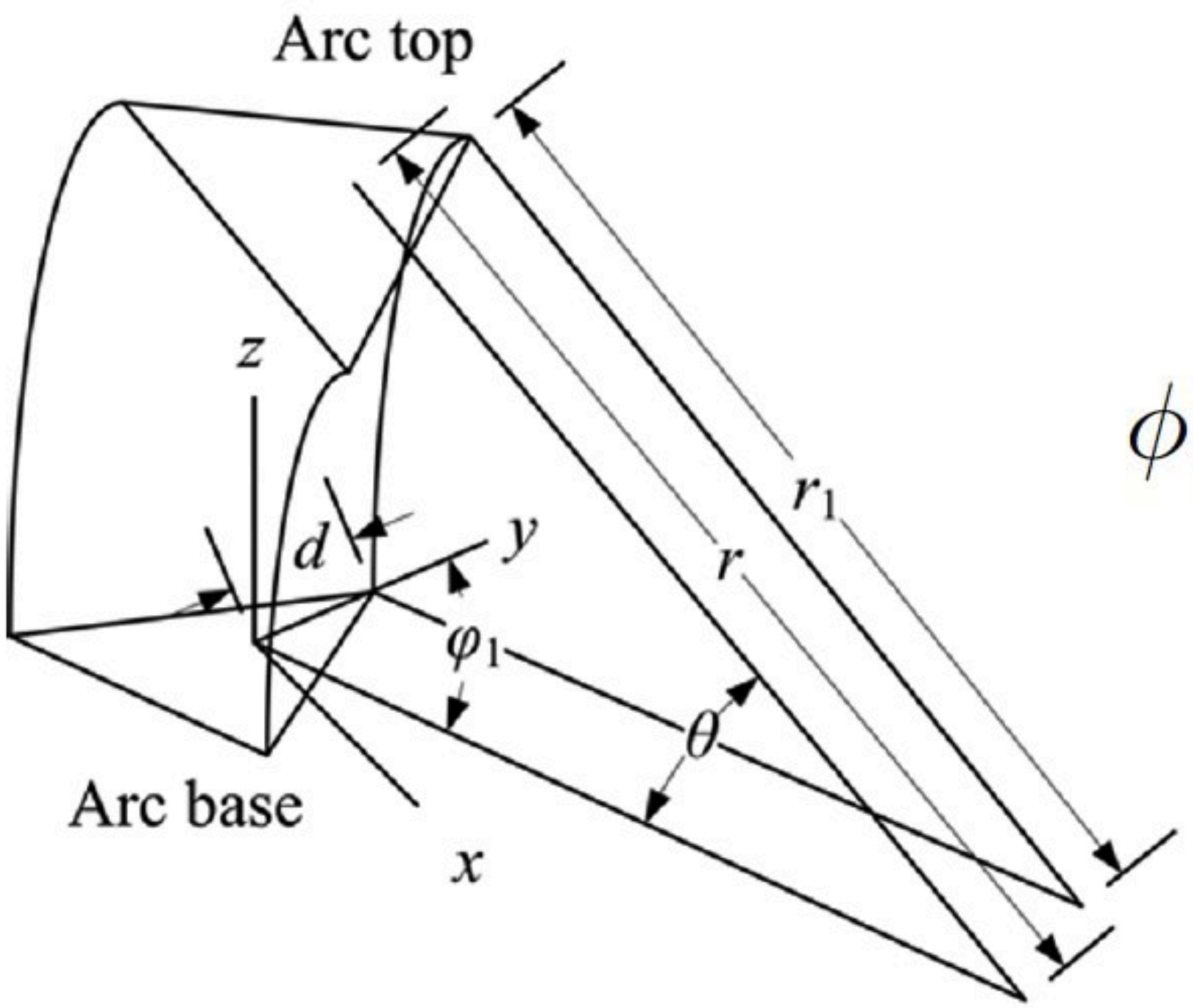
$$T = \underbrace{\begin{bmatrix} R_z(\phi) & 0 \\ 0 & 1 \end{bmatrix}}_{\text{Rotation}} \underbrace{\begin{bmatrix} R_y(\theta) & \boldsymbol{p} \\ 0 & 1 \end{bmatrix}}_{\text{Inplane transformation}}$$

$$T = \begin{bmatrix} \cos\phi\ \cos\kappa s & -\sin\phi & \cos\phi\ \sin\kappa s & \frac{\cos\phi\ (1-\cos\kappa s)}{\kappa} \\ \sin\phi\ \cos\kappa s & \cos\phi & \sin\phi\ \sin\kappa s & \frac{\sin\phi\ (1-\cos\kappa s)}{\kappa} \\ -\sin\kappa s & 0 & \cos\kappa s & \frac{\sin\kappa s}{\kappa} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Robot-Specific Mapping



Robot-Specific Mapping: A Geometry Problem



$$\ell = l_i + \theta d \cos \phi_i$$

$$\phi(\boldsymbol{q}) = \tan^{-1}\left(\frac{\sqrt{3}(l_2 + l_3 - 2l_1)}{3(l_2 - l_3)}\right)$$

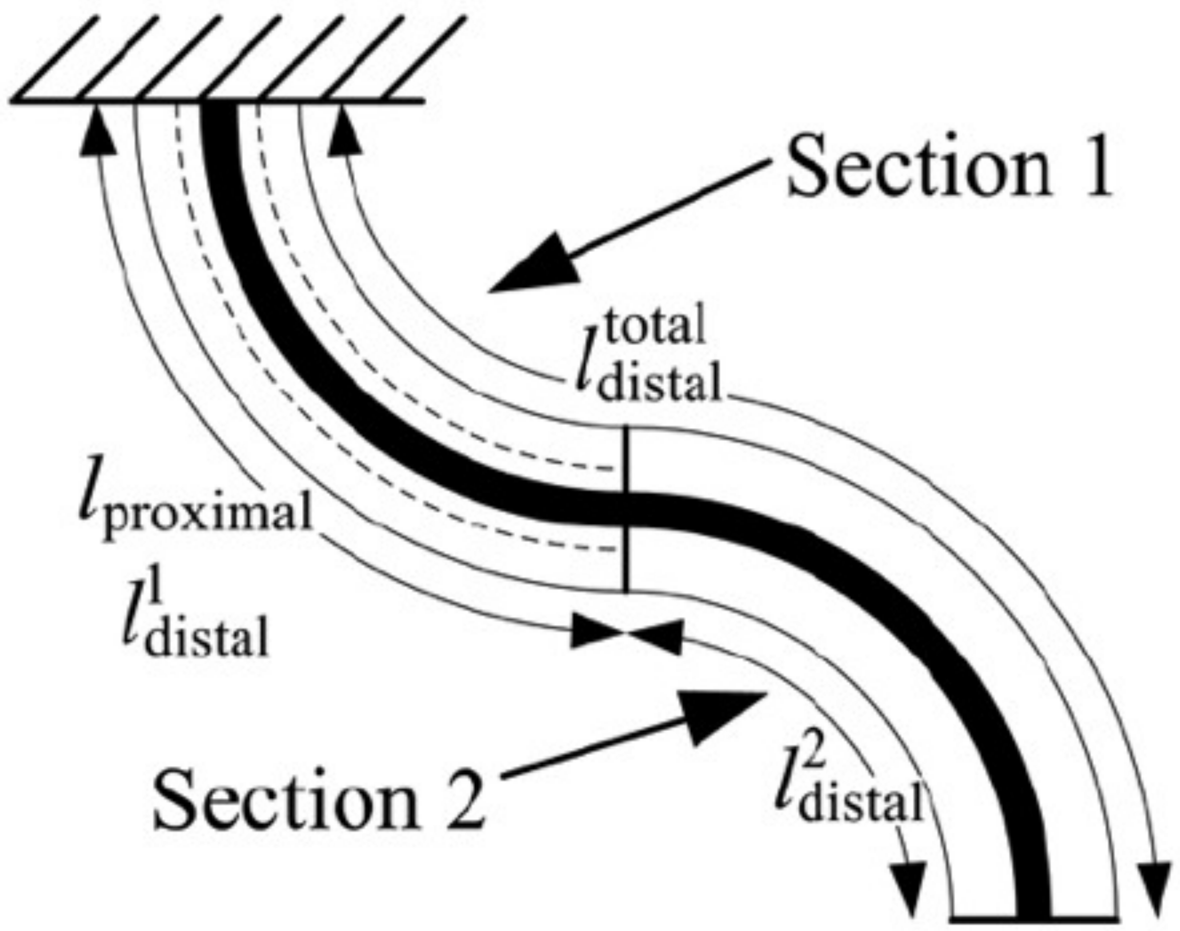
$$\ell(\boldsymbol{q}) = \frac{l_1 + l_2 + l_3}{3}$$

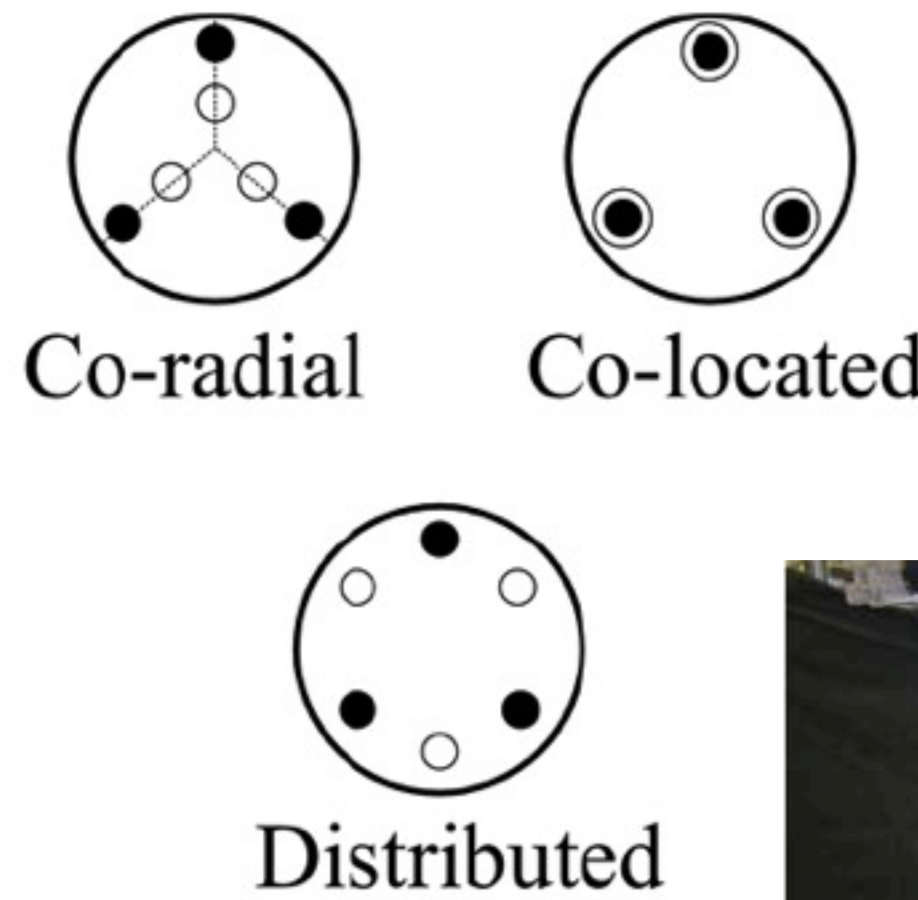
$$\kappa(\boldsymbol{q}) = \frac{2\sqrt{l_1^2 + l_2^2 + l_3^2 - l_1 l_2 - l_1 l_3 - l_2 l_3}}{d(l_1 + l_2 + l_3)}$$

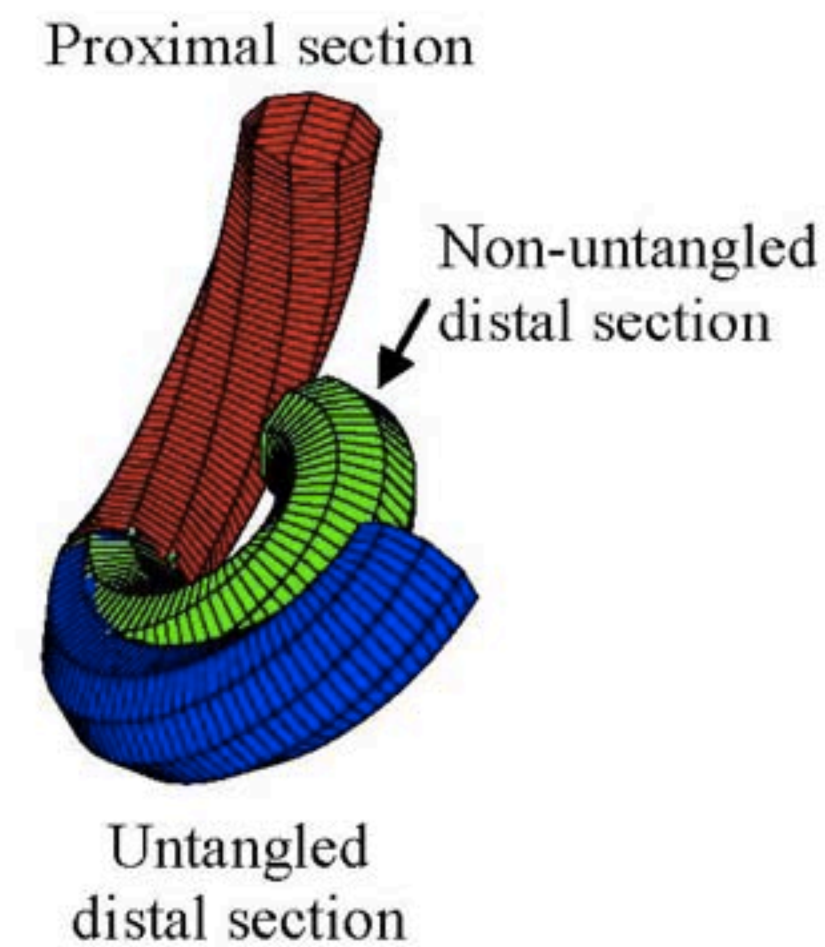
4 and 3 wire cases where wires are don’t follow arc reviewed in:

R. J. Webster III and B. A. Jones. Design and Kinematic Modeling of Constant Curvature Continuum Robots: A Review. Int’l Journal of Robotics Research, 29(13), 1661-1683, 2010.

Multi-Section Coupling



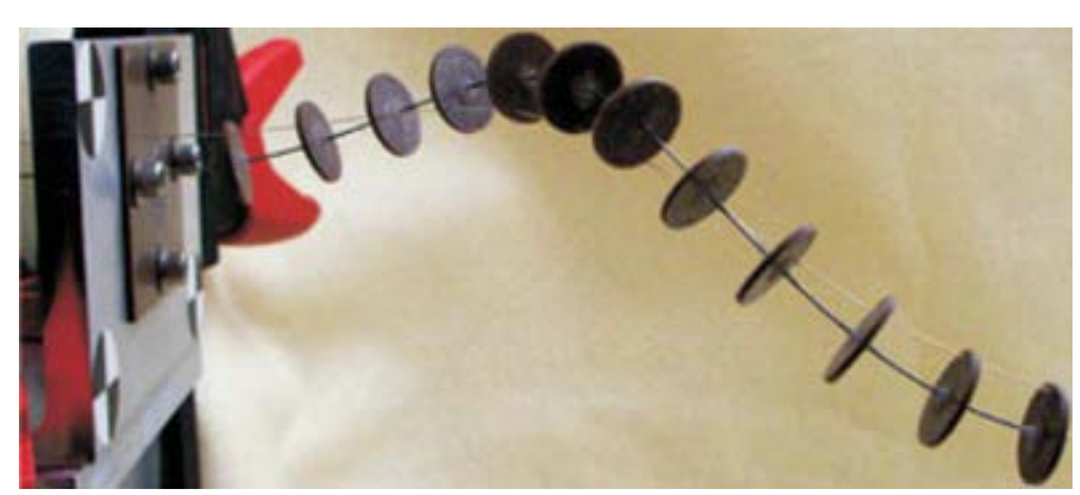


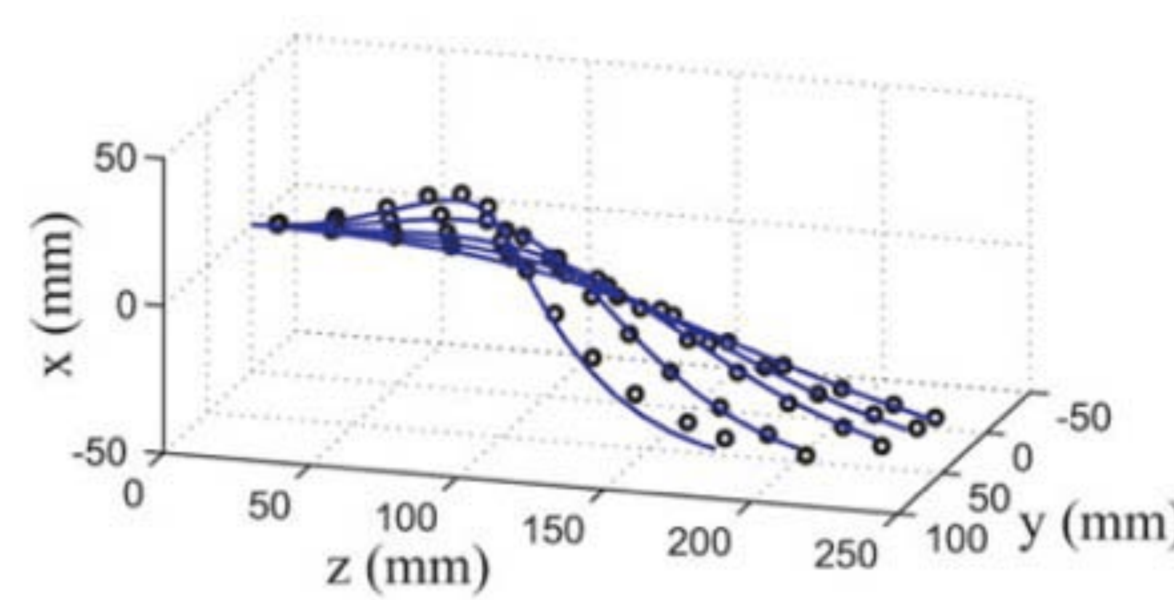


- Co-Located: No Coupling
- Co-Radial: Easier
- Distributed: Iterative process: “tangle-untangle”

Jones and Walker, "Practical Kinematics for Real-Time Implementation of Continuum Robots," TRO 2006.

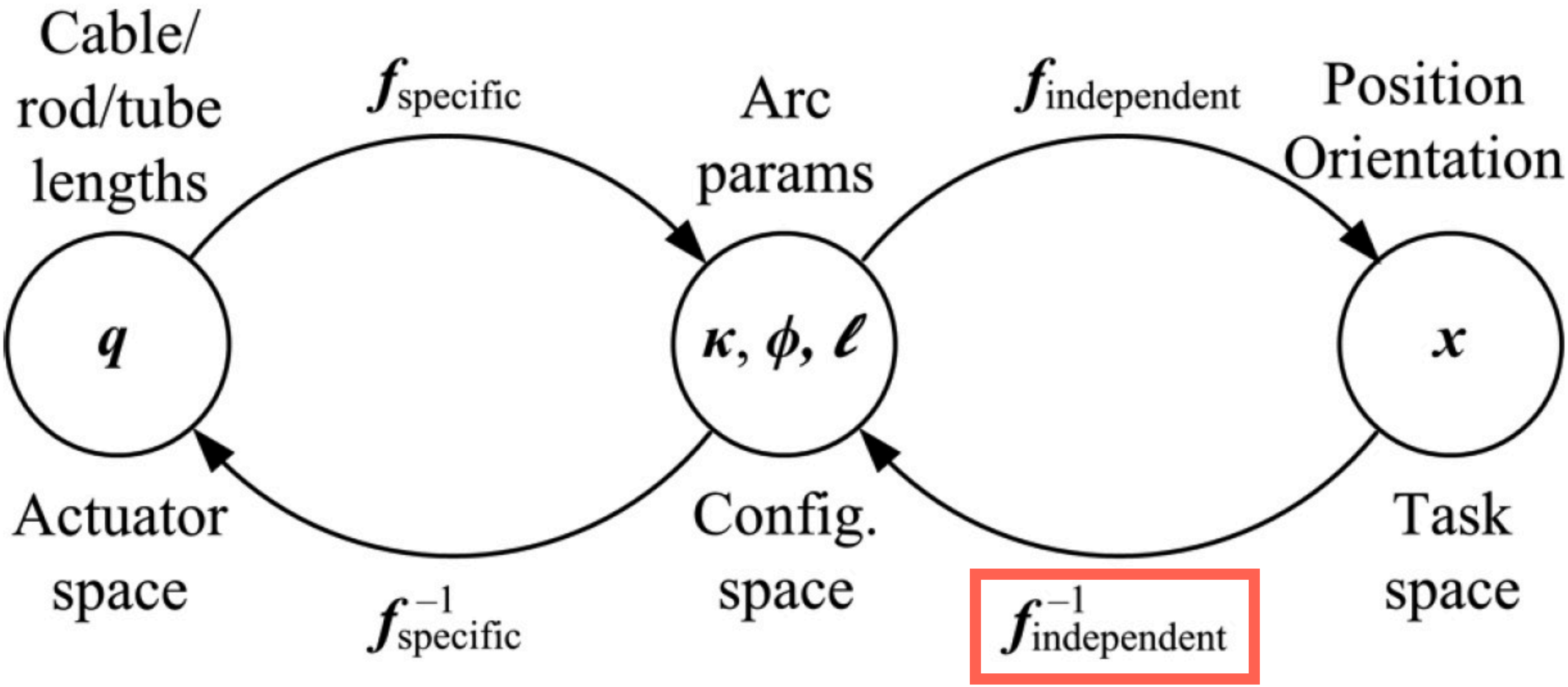
- General method for any number of wires, general routing, external loads



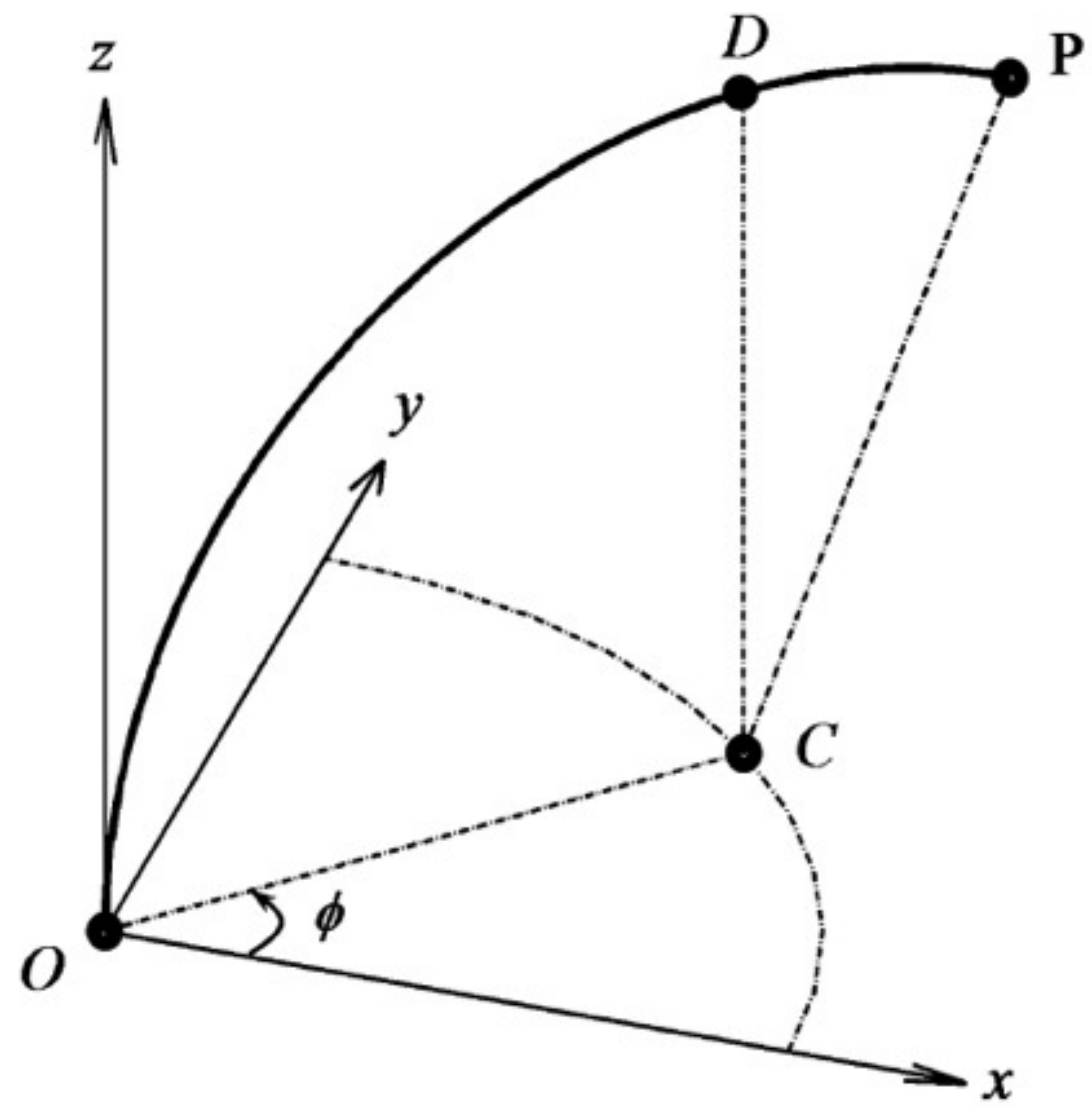


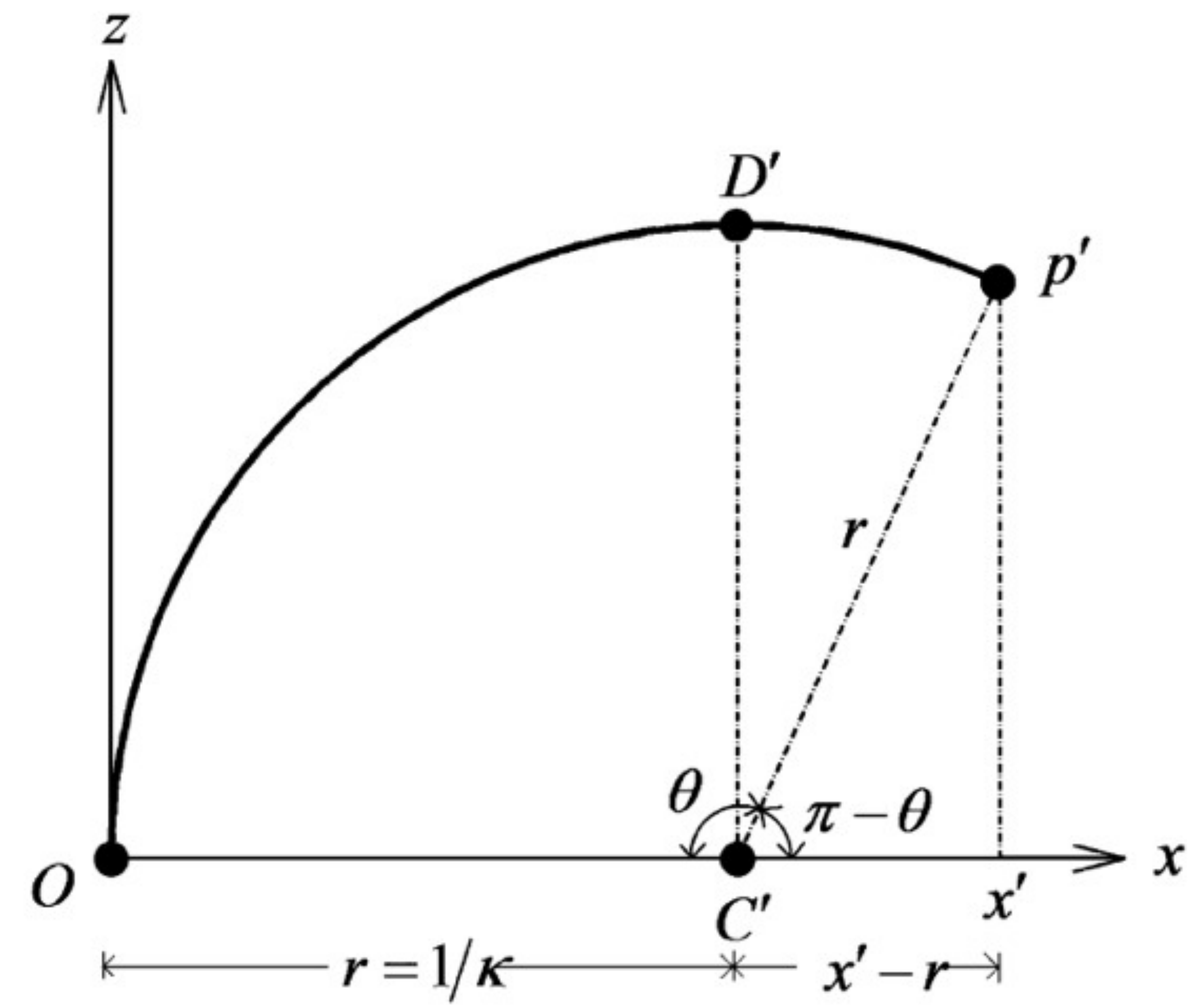
Rucker and Webster “Statics and Dynamics of Continuum Robots With General Tendon Routing and External Loading,” TRO 2011.

Inverse Kinematics



Inverse Kinematics: Single Section





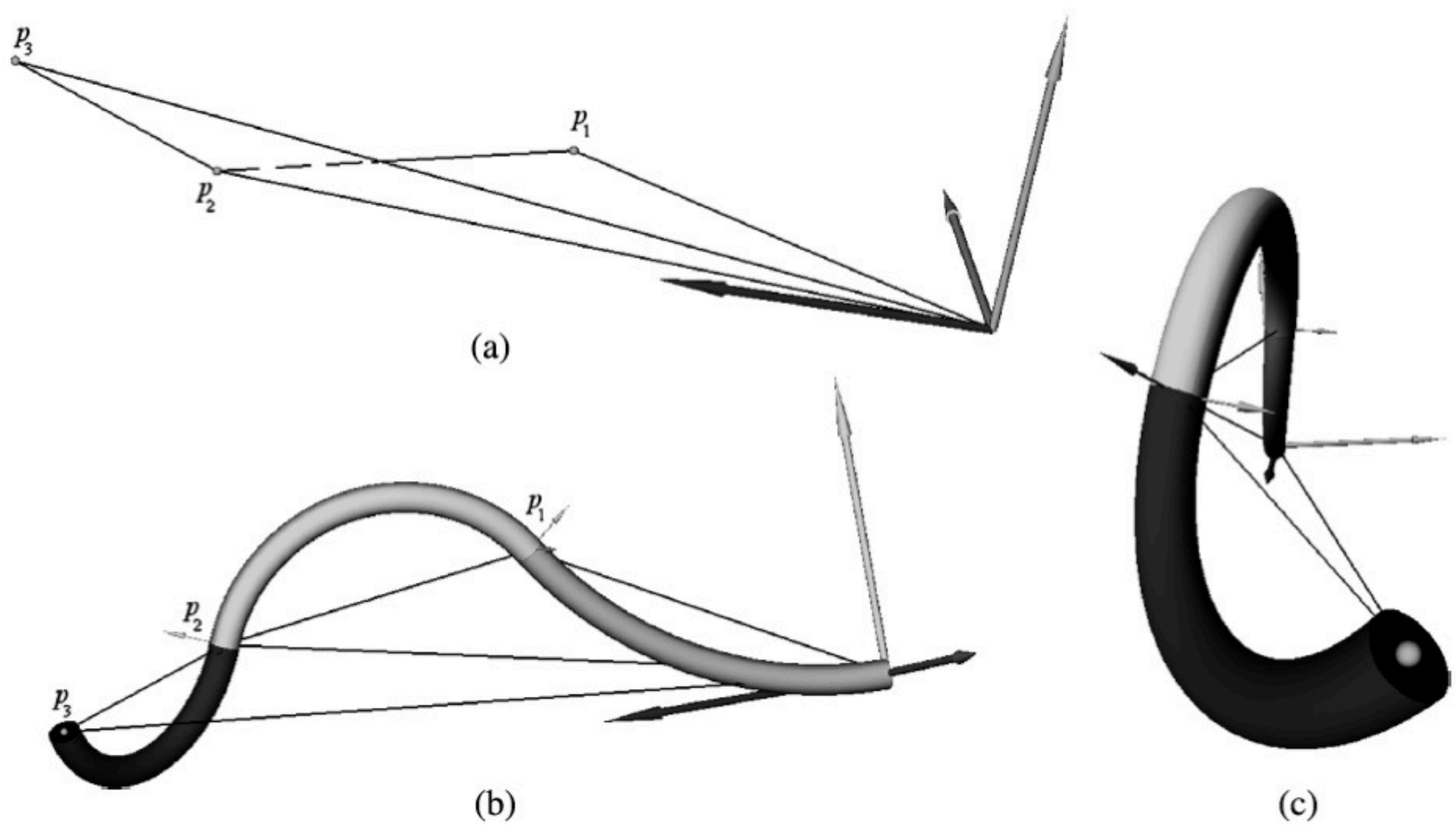
$$\phi = \tan^{-1}\left(\frac{y}{x}\right) \qquad \kappa = \frac{2\sqrt{x^2+y^2}}{x^2+y^2+z^2}$$

$$\theta = \begin{cases} \cos^{-1}(1-\kappa\sqrt{x^2+y^2}), & z > 0 \\ 2\pi - \cos^{-1}(1-\kappa\sqrt{x^2+y^2}), & z \leqslant 0 \end{cases}$$

Neppalli, Csencsits, Jones, and Walker, “Closed-form inverse kinematics for continuum manipulators,” Advanced Robotics, 23: 2077–2091, 2009.

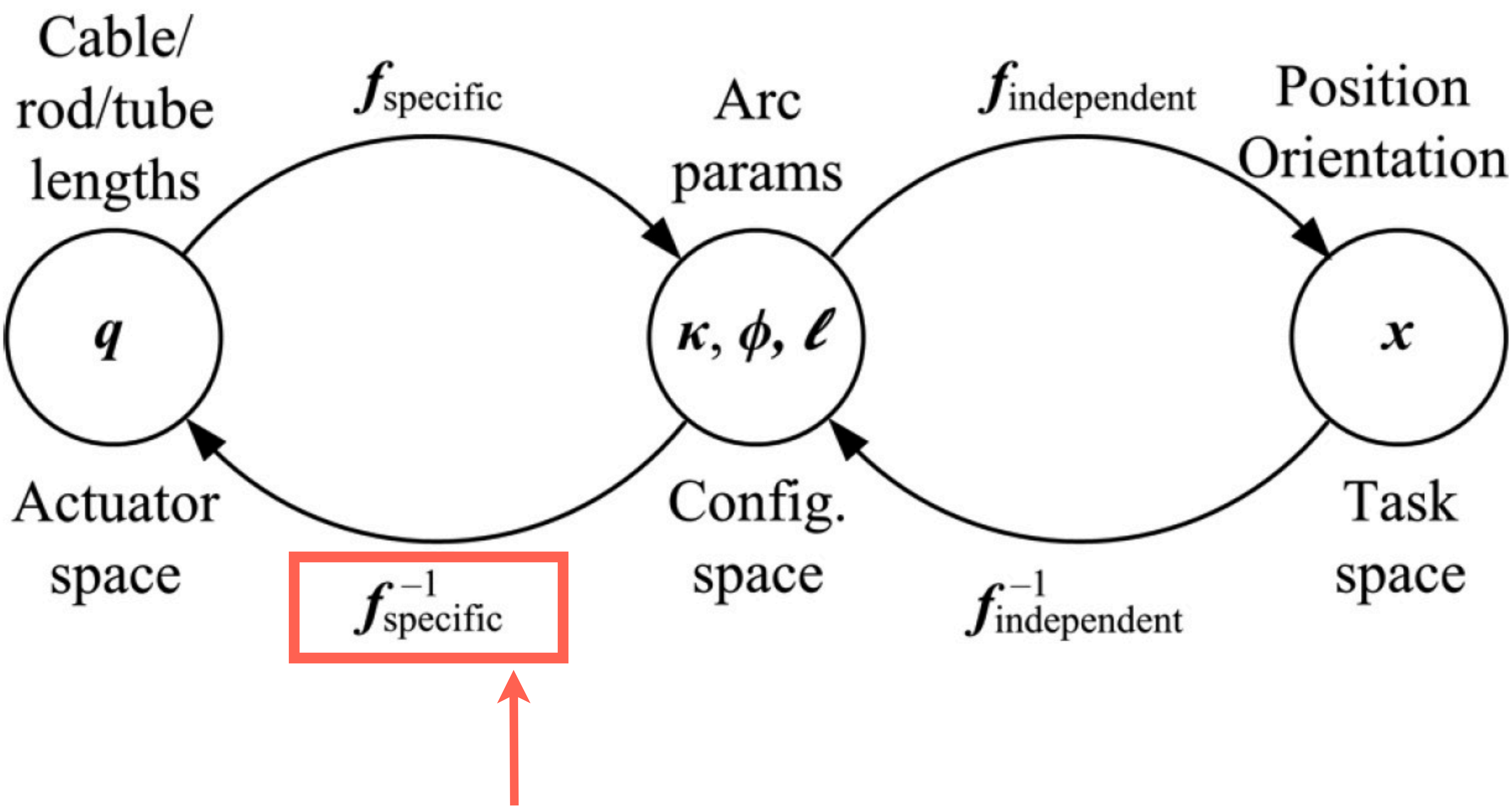
Inverse Kinematics: Multi-Section

- Model the robot as a series of ball in socket joints connected by rigid links.
- Apply algorithm from: Han and Rudolph, "A unified geometric approach for inverse kinematics of a spatial chain with spherical joints," ICRA 2007.
- Solve several single-section problems



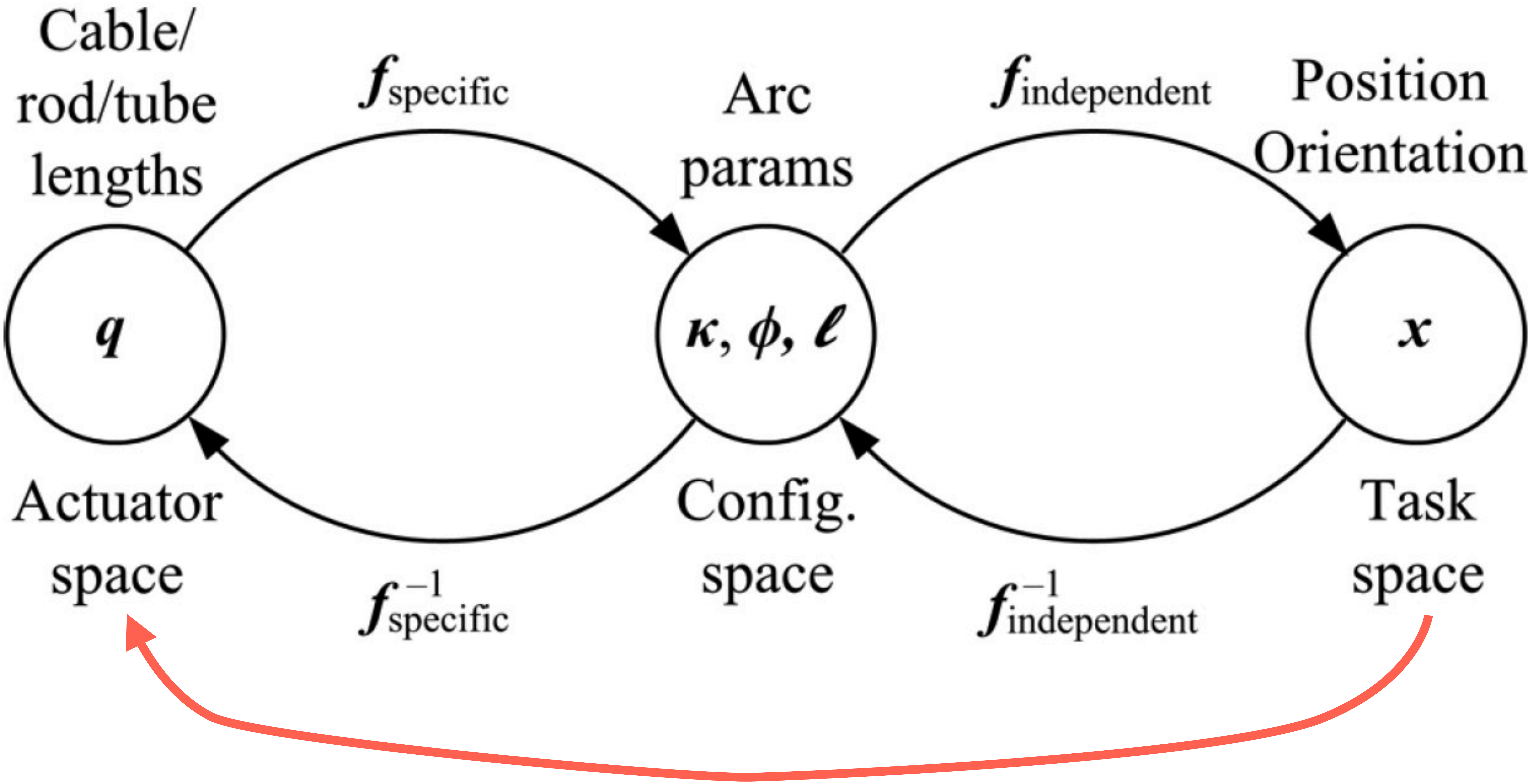
Neppalli, Csencsits, Jones, and Walker, "Closed-form inverse kinematics for continuum manipulators," Advanced Robotics, 23: 2077–2091, 2009.

Inverse Kinematics



Depends on the robot. Try to invert your geometry problem.

Inverse Kinematics



Alternative: Use the Jacobian to Servo the Robot, Solving Inverse Kinematics Iteratively

Jacobian of Independent Mapping

- Single Section

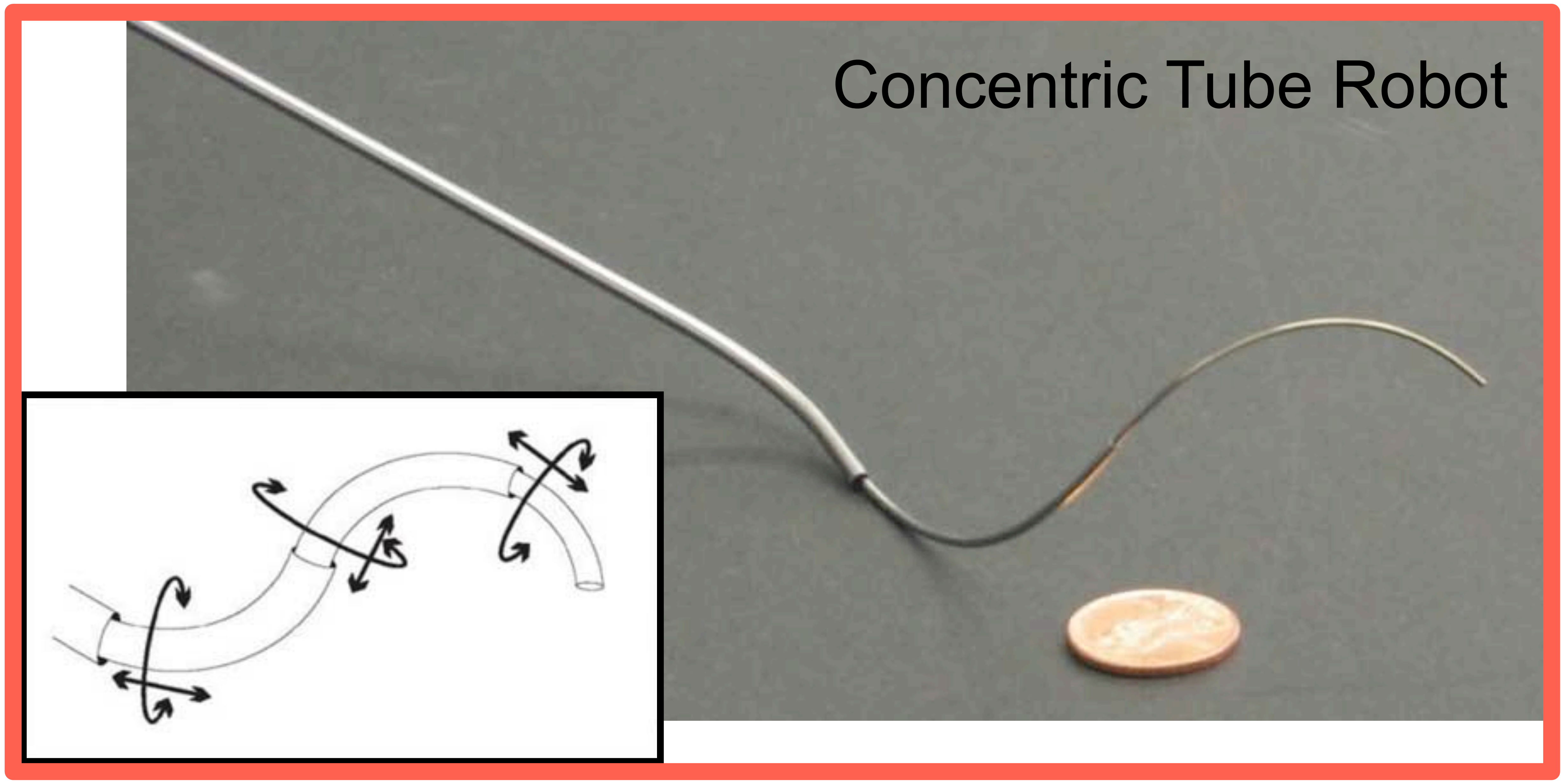
$$V_j^s = \underbrace{\begin{bmatrix} \cos\Delta\phi_j\ (\cos(\kappa_j\ell_j)-1)/\kappa_j^2 & 0 & 0 \\ \sin\Delta\phi_j\ (\cos(\kappa_j\ell_j)-1)/\kappa_j^2 & 0 & 0 \\ -(\sin\ (\kappa_j\ell_j)-\kappa_j\ell_j)/\kappa_j^2 & 0 & 1 \\ -\ell_j\ \sin\Delta\phi_j & 0 & -\kappa_j\ \sin\Delta\phi_j \\ \ell_j\ \cos\Delta\phi_j & 0 & \kappa_j\ \cos\Delta\phi_j \\ 0 & 1 & 0 \end{bmatrix}}_{J_j^s} \begin{bmatrix} \dot{\kappa}_j \\ \Delta\dot{\phi}_j \\ \dot{\ell}_j \end{bmatrix}$$

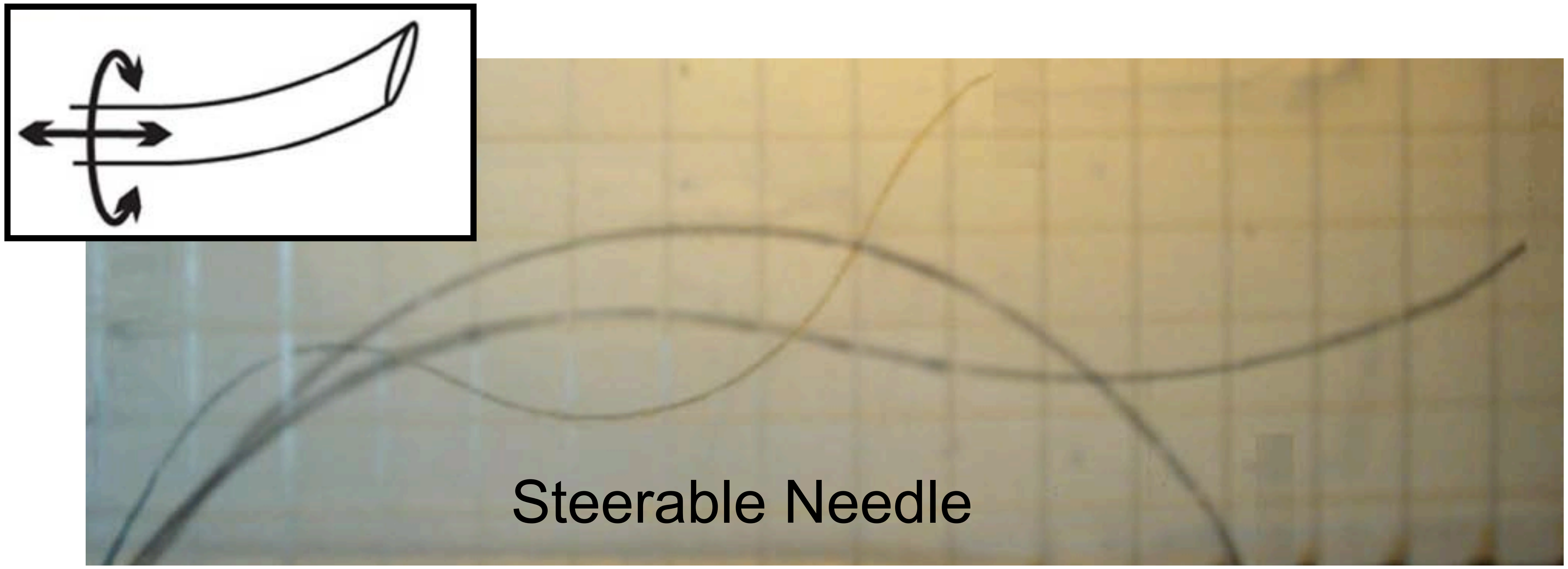
- Multi-Section

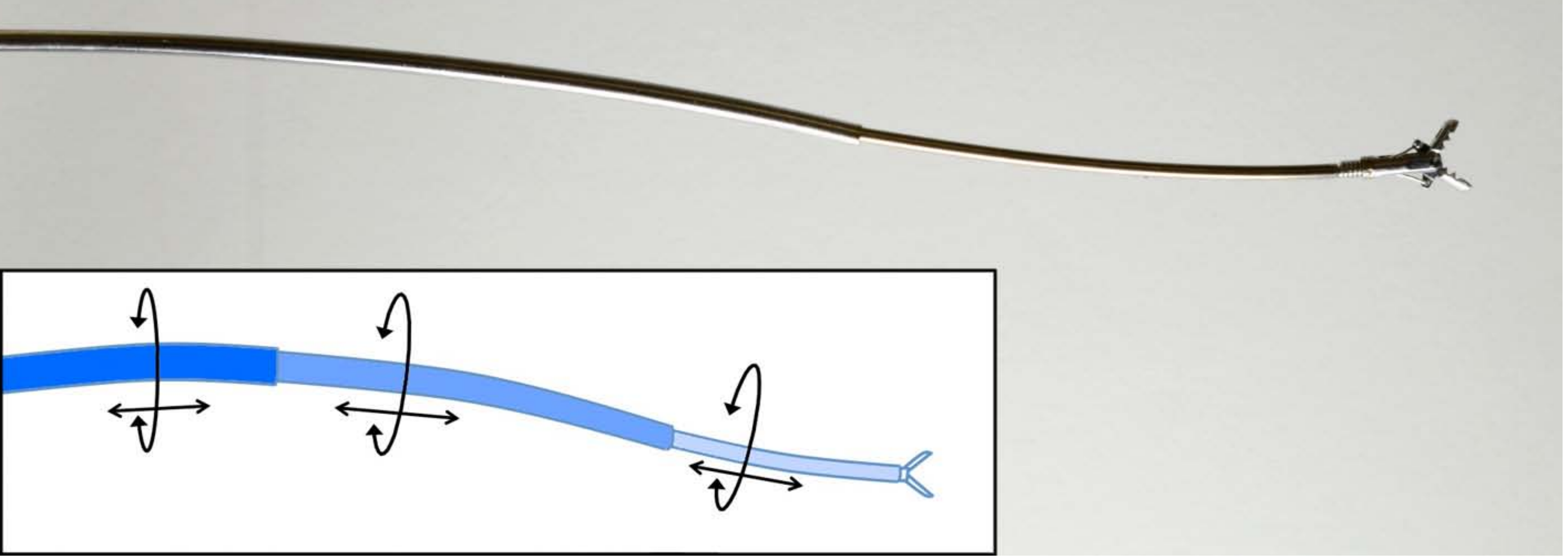
$$J_{\text{robot}}^s = \left[J_0\ \text{Ad}_{T_0} J_1\ \text{Ad}_{T_{01}} J_2\ \cdots\ \text{Ad}_{T_{0(m-1)}} J_m \right]$$

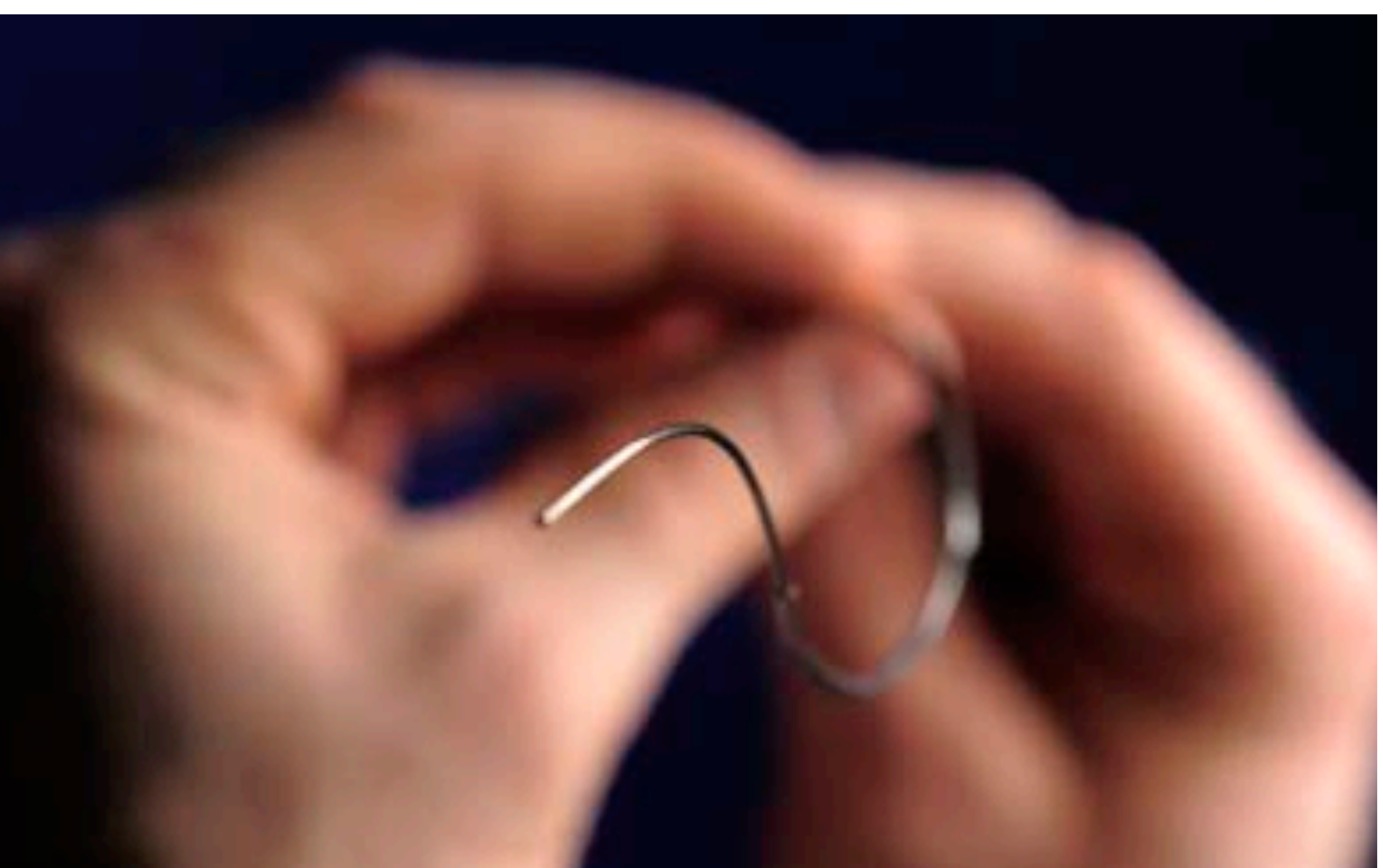
Webster and Jones, “Design and Kinematic Modeling of Constant Curvature Continuum Robots: A Review,” IJRR 2010.

Examples



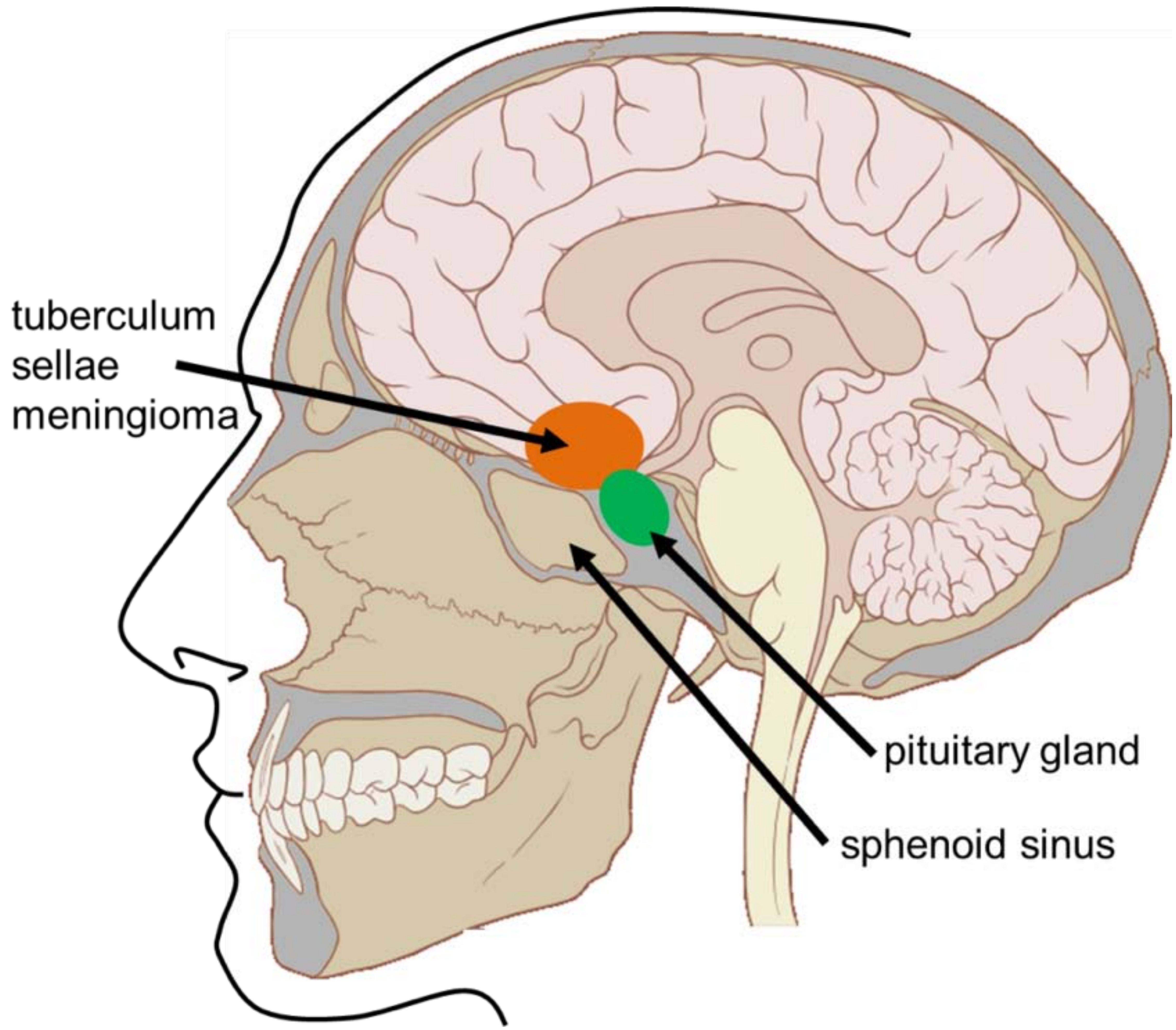


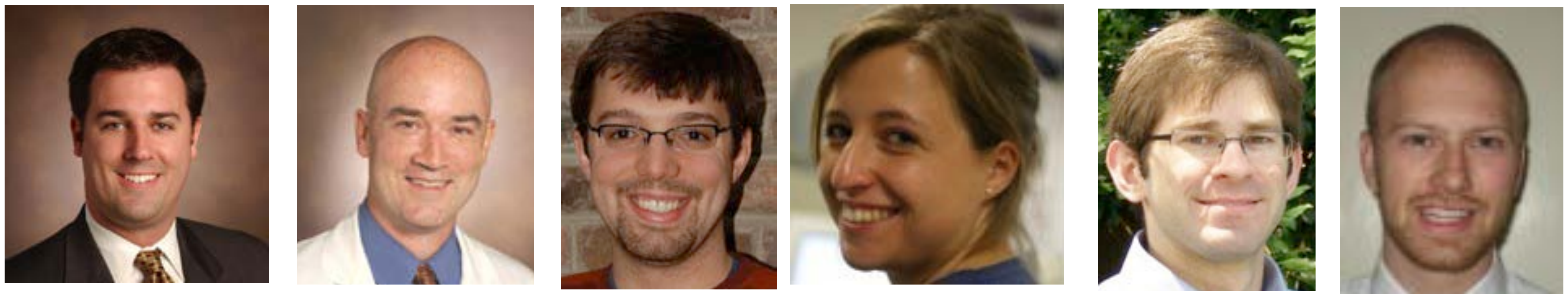




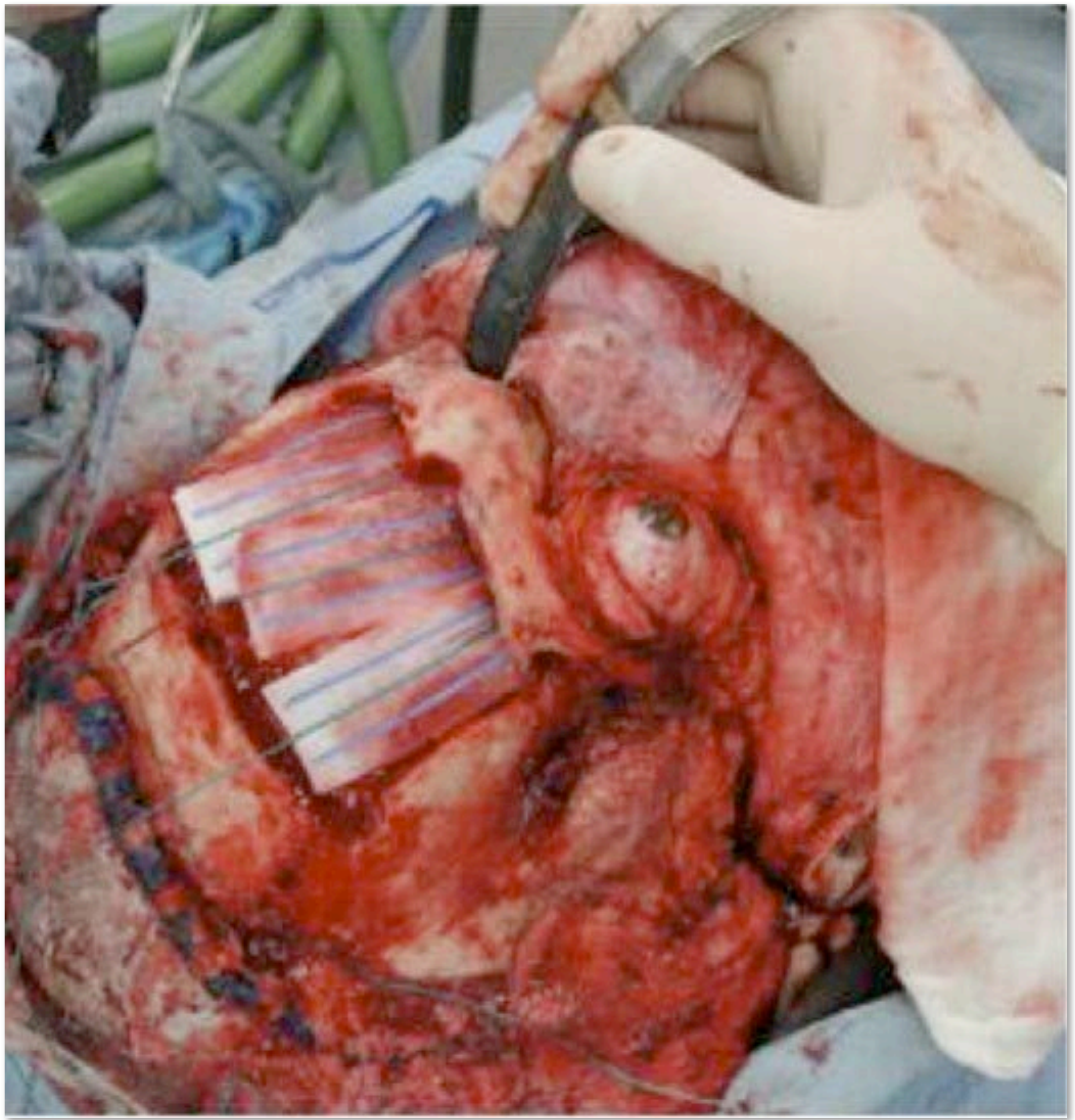
Endonasal Skull Base Surgery

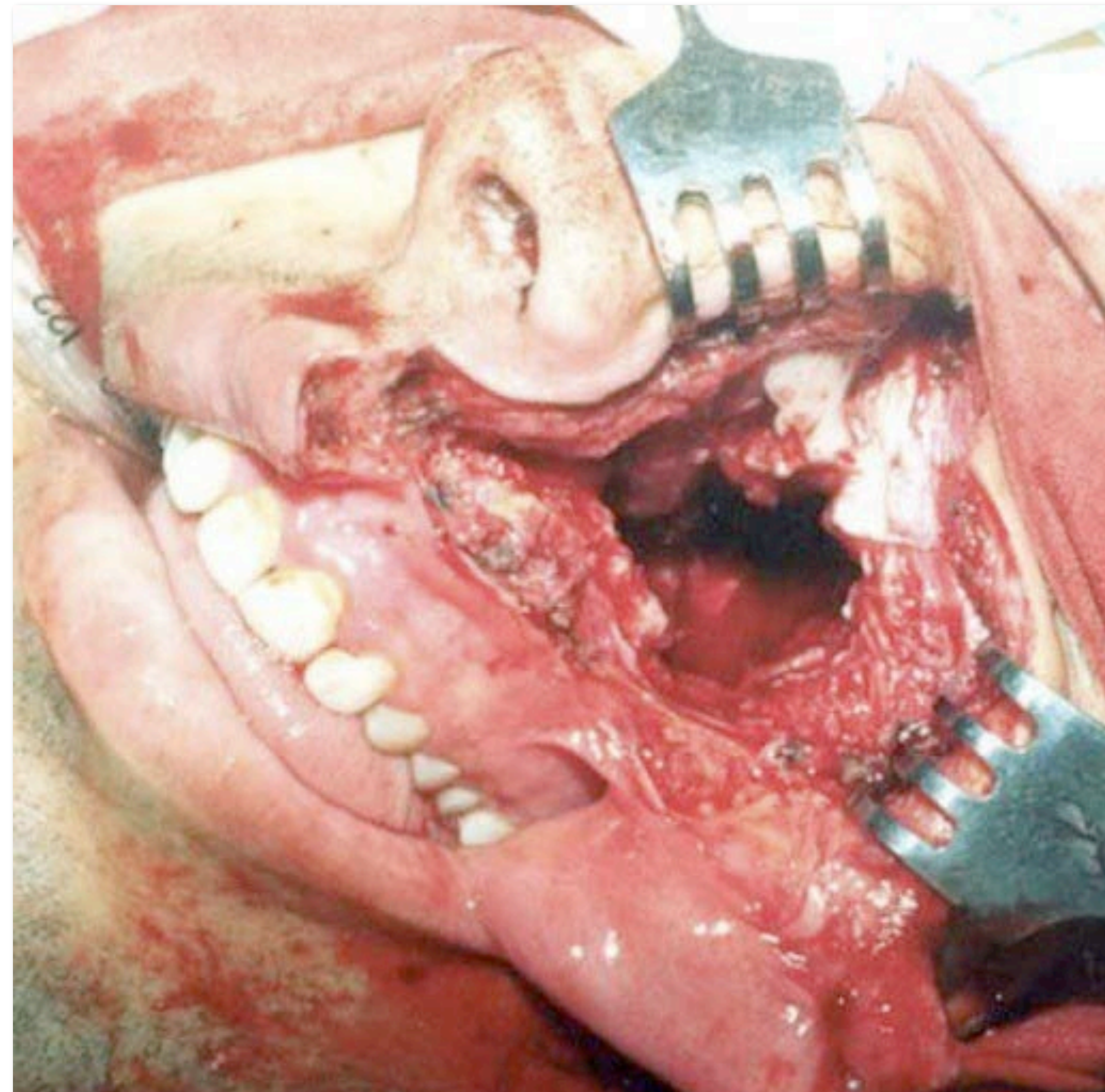
- 1 of 5 people will have a pituitary tumor
- 1 in 120 need surgery
- 39% of brain tumors arise in tuberculum sellae





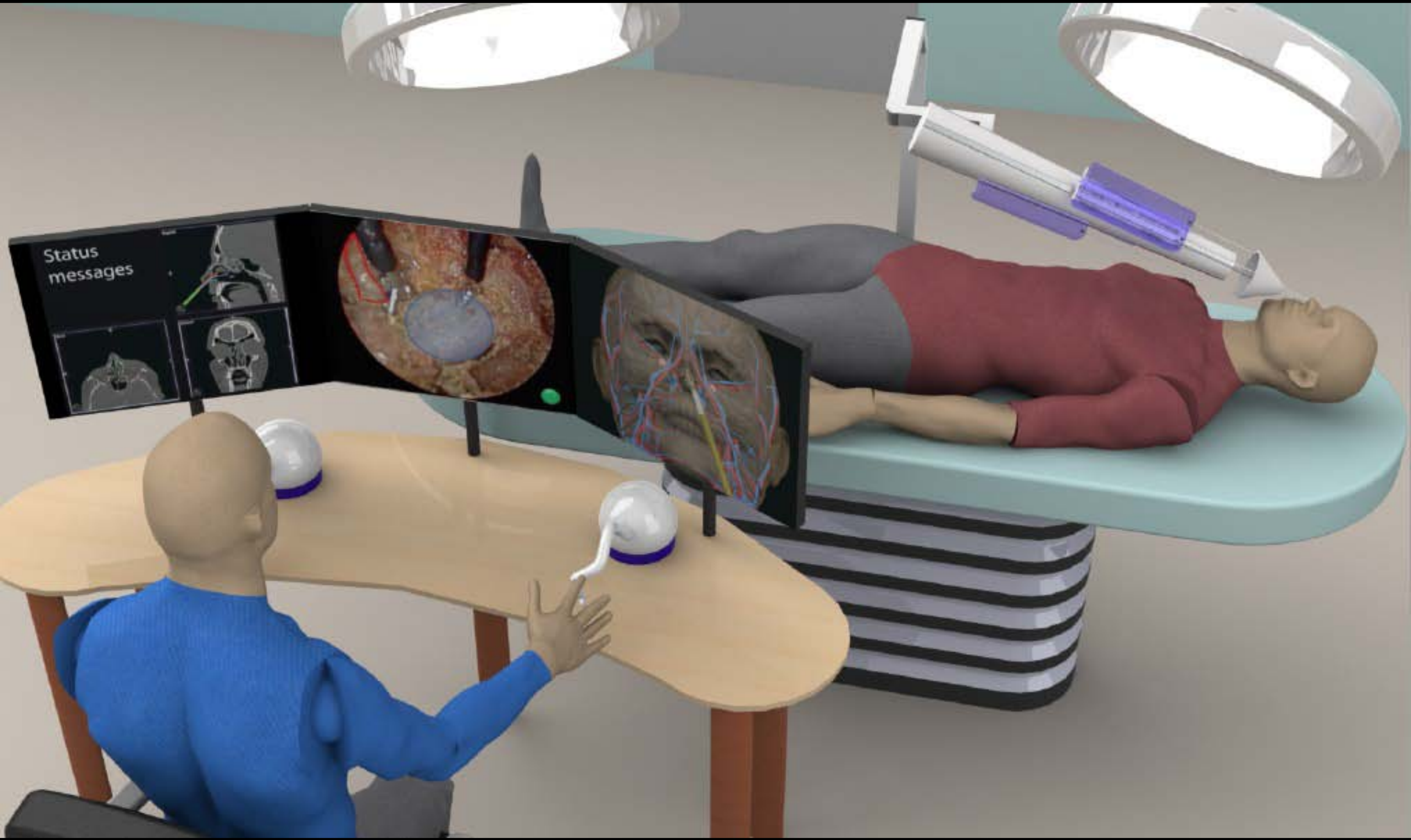
Traditional Approaches





Can We use da Vinci?

Our System Concept



Burgner, Rucker, Gilbert, Swaney, Russell, Weaver, and Webster, "A Telerobotic System for Transnasal Surgery," TMECH (In Press).

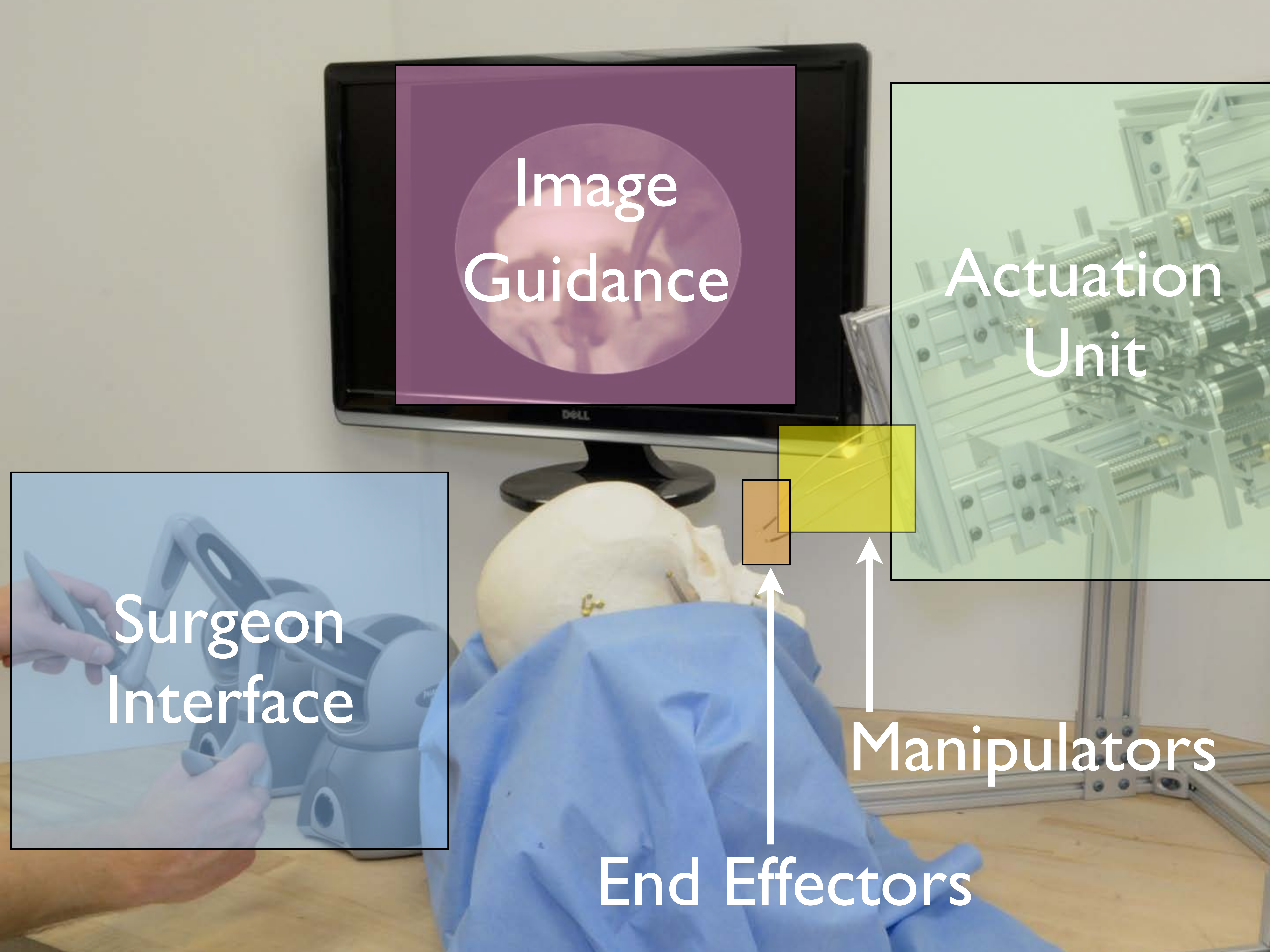


Image
Guidance
Actuation
Unit
Surgeon
Interface
Manipulators
End Effectors

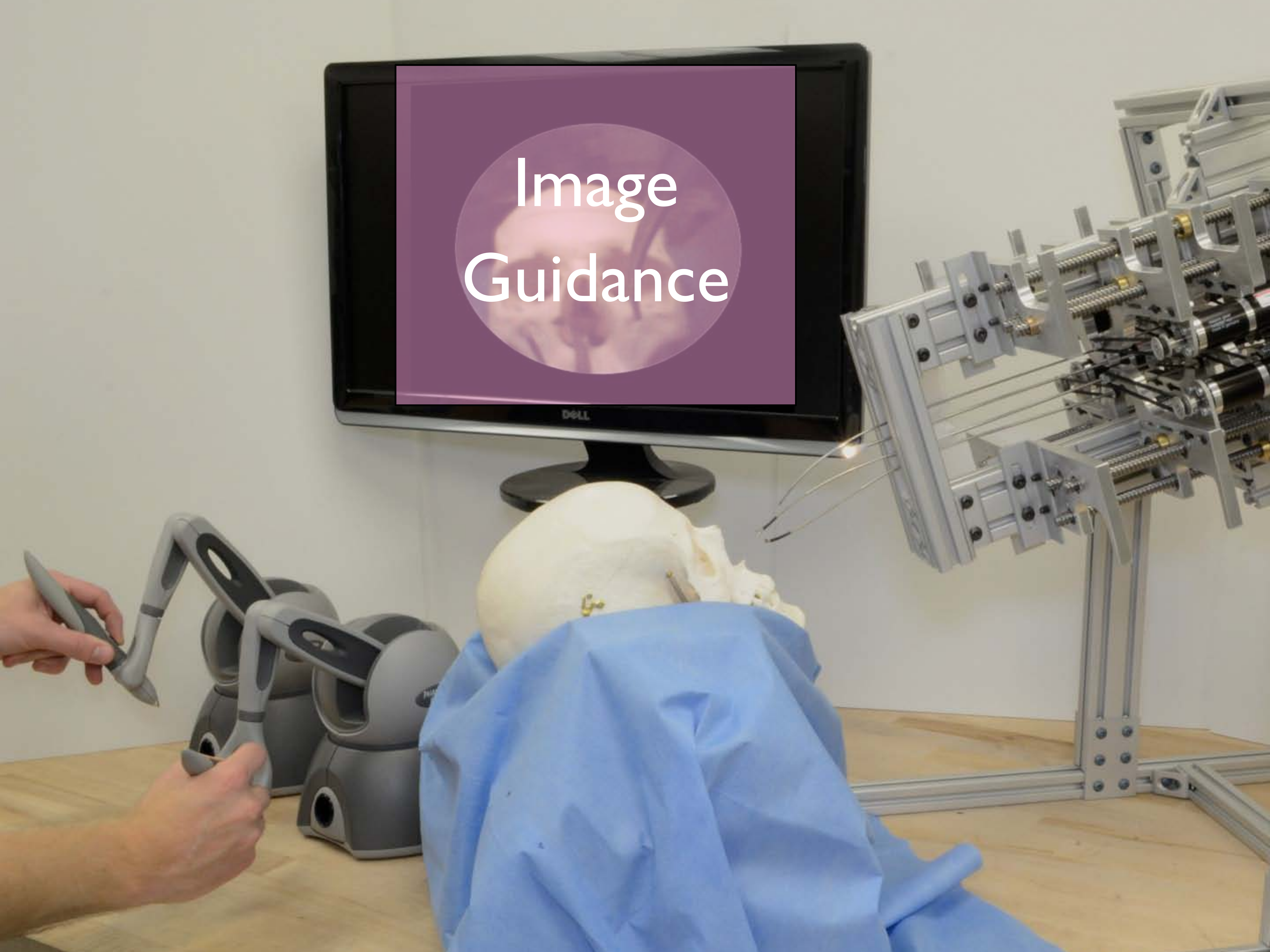
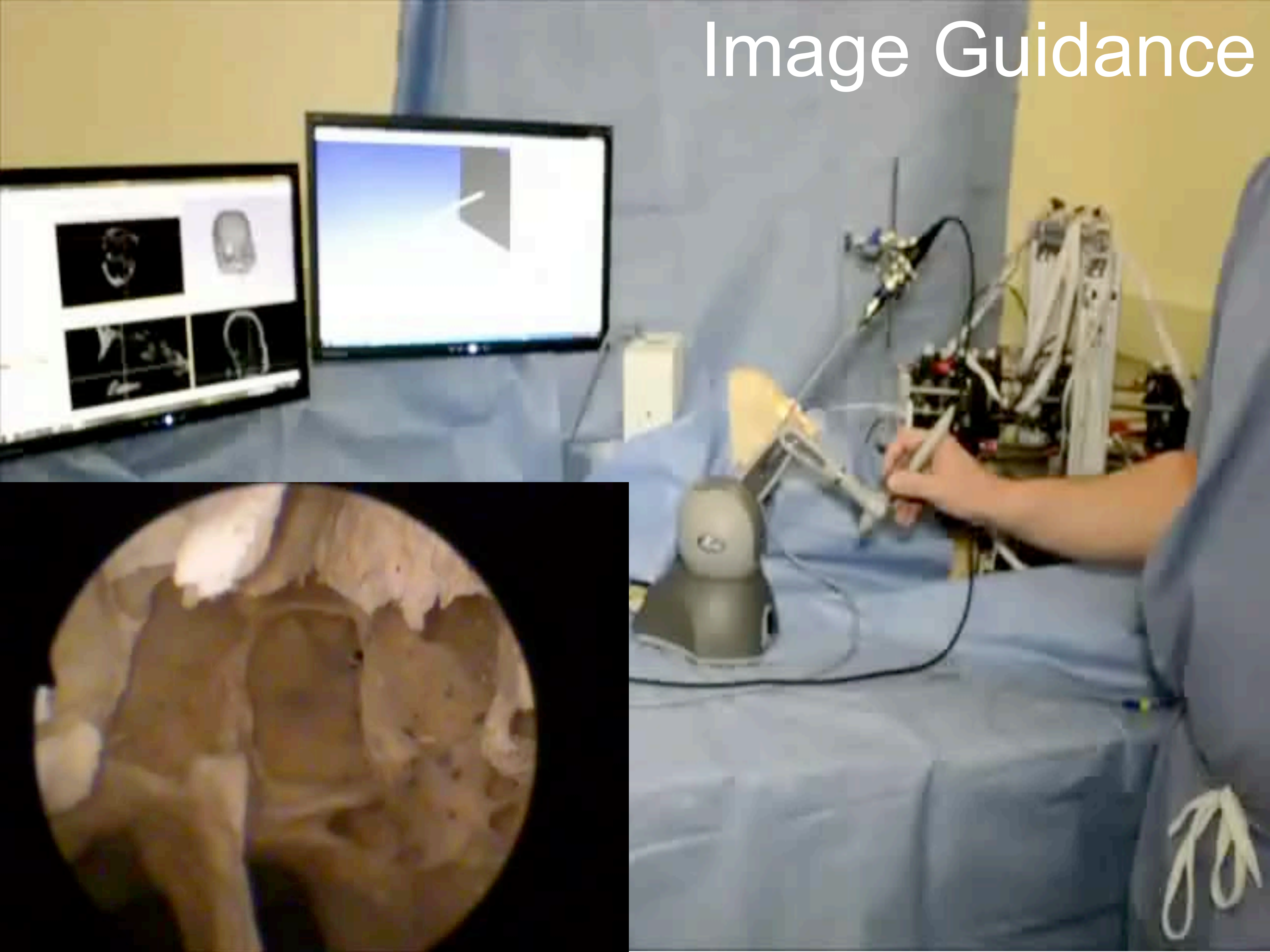
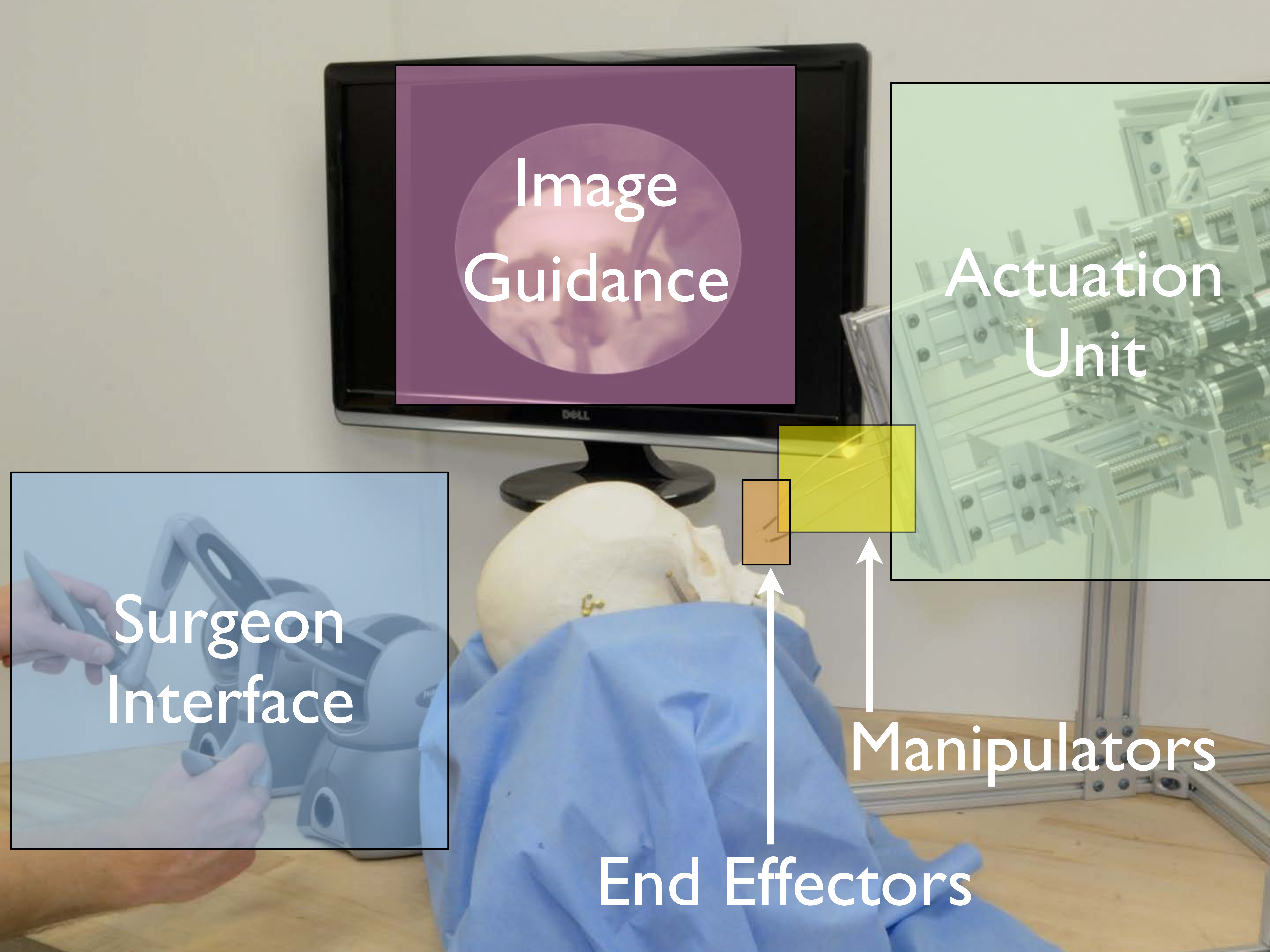


Image
Guidance

Image Guidance

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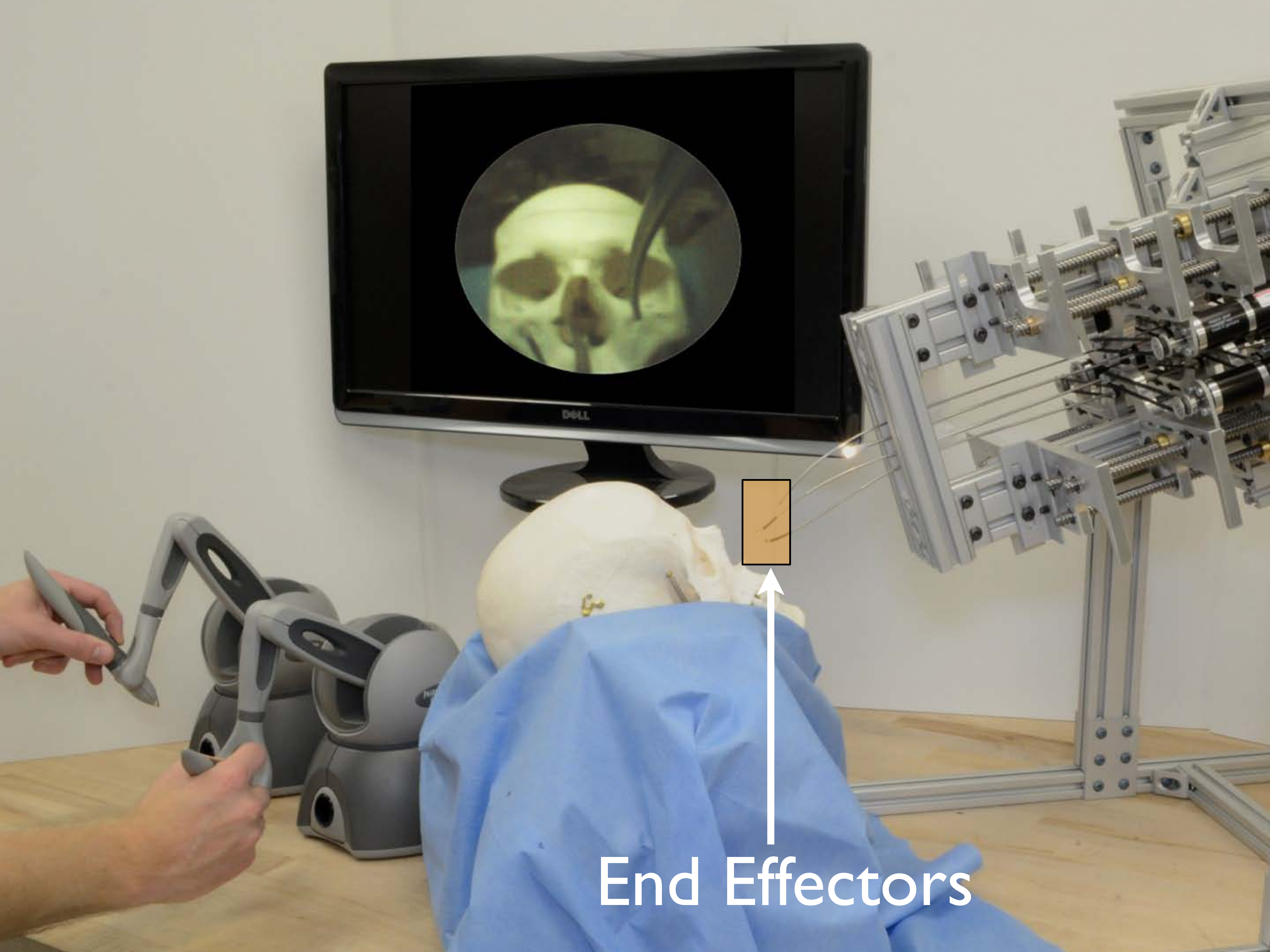
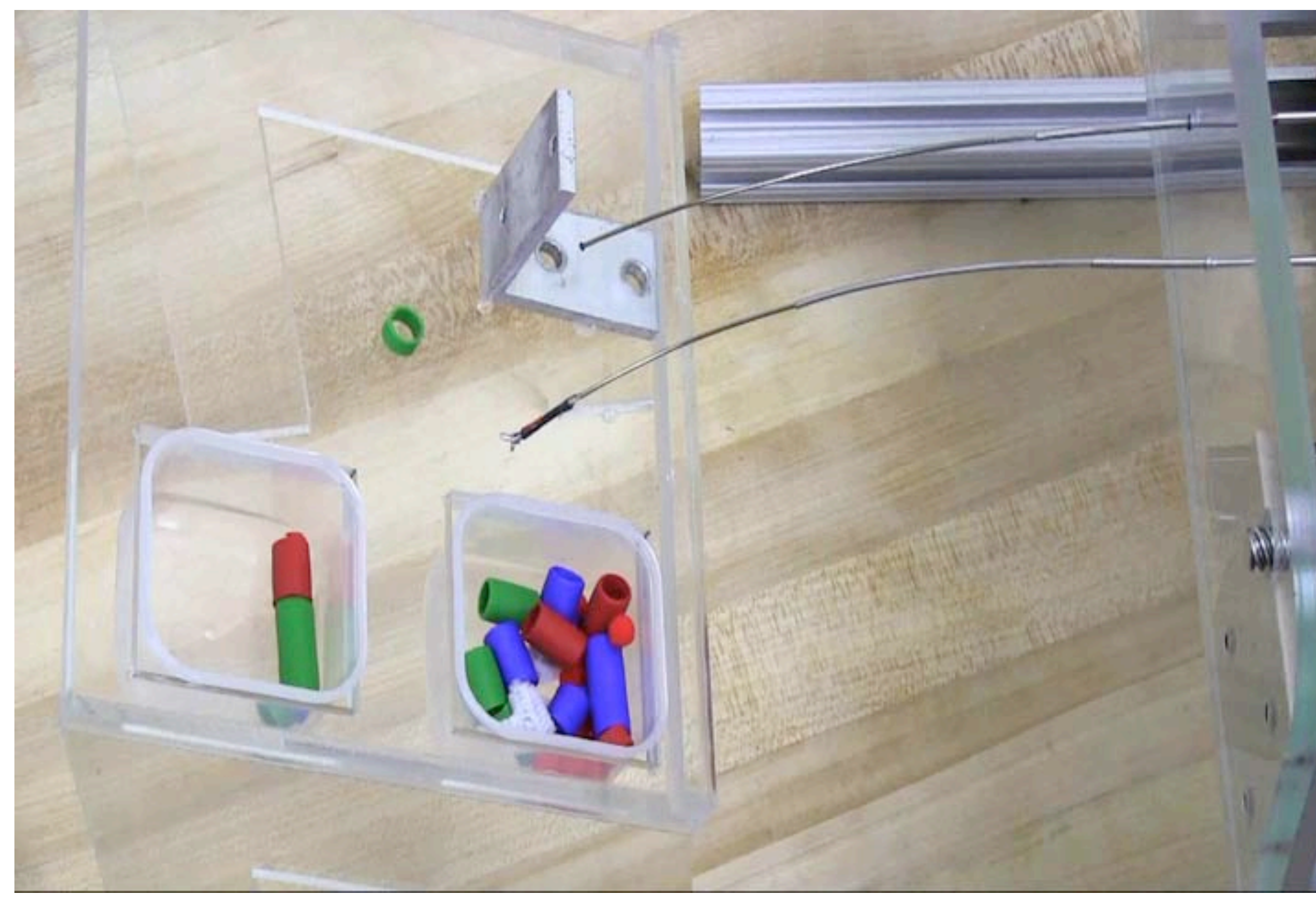
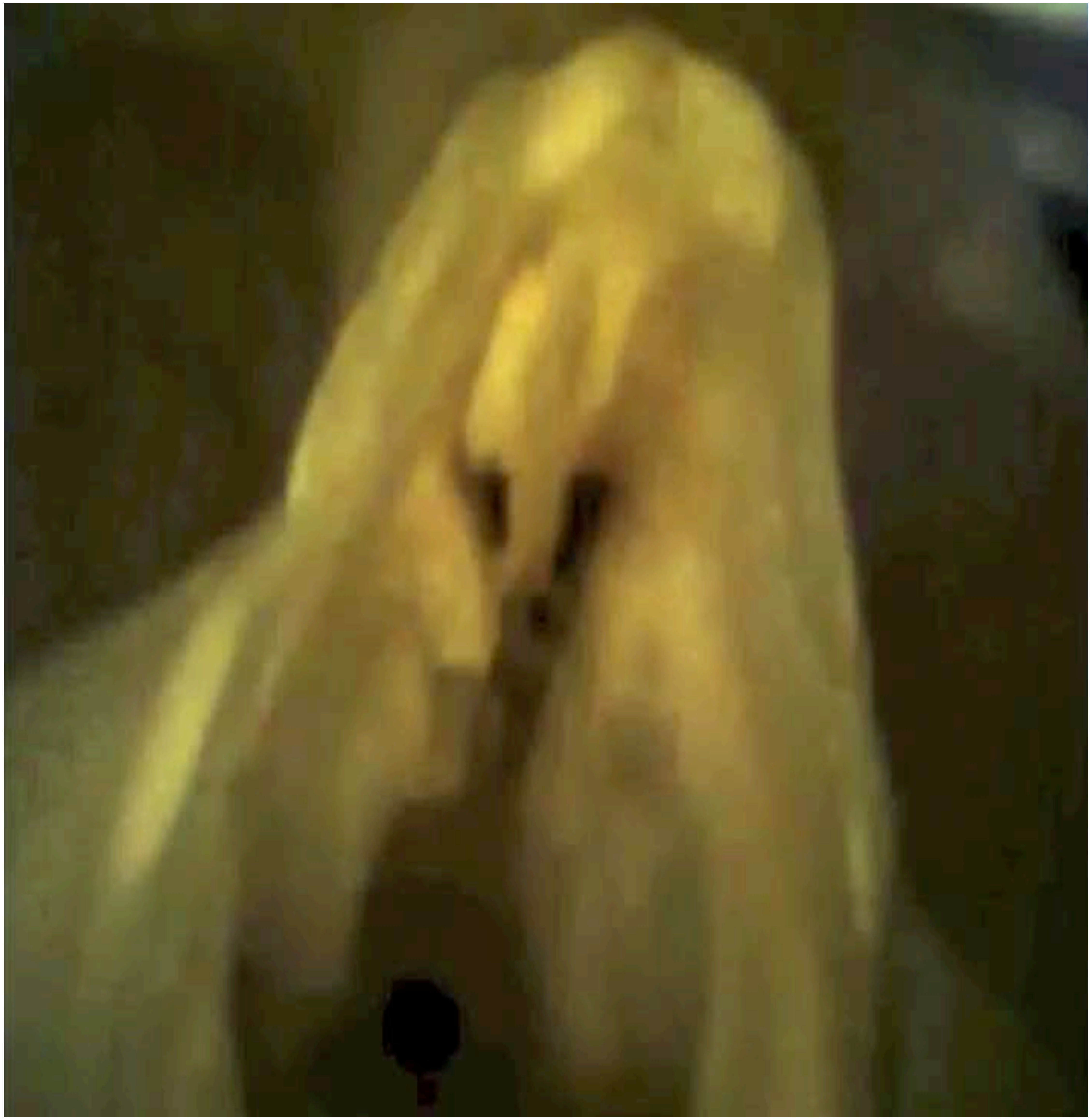
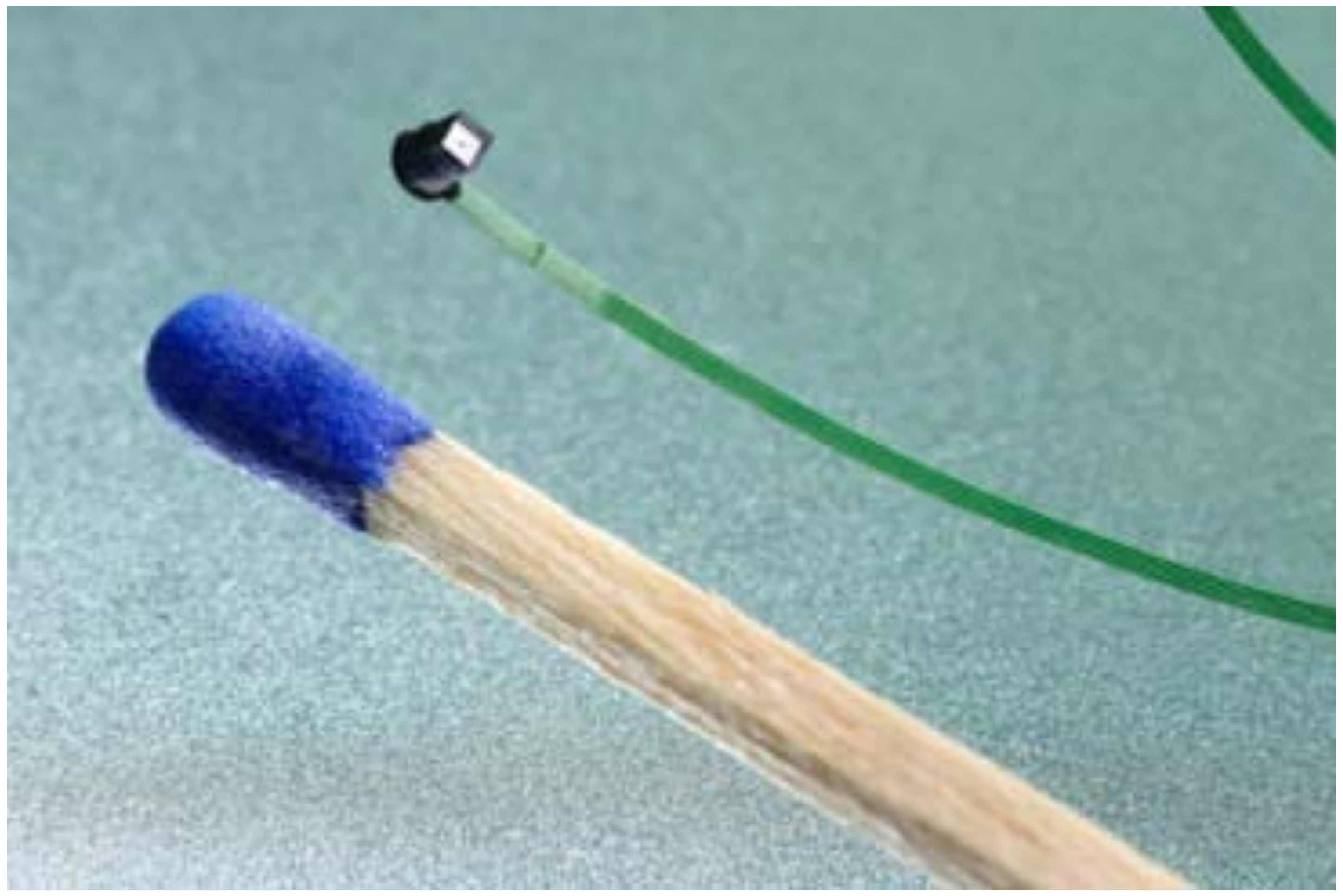

DELL
End Effectors

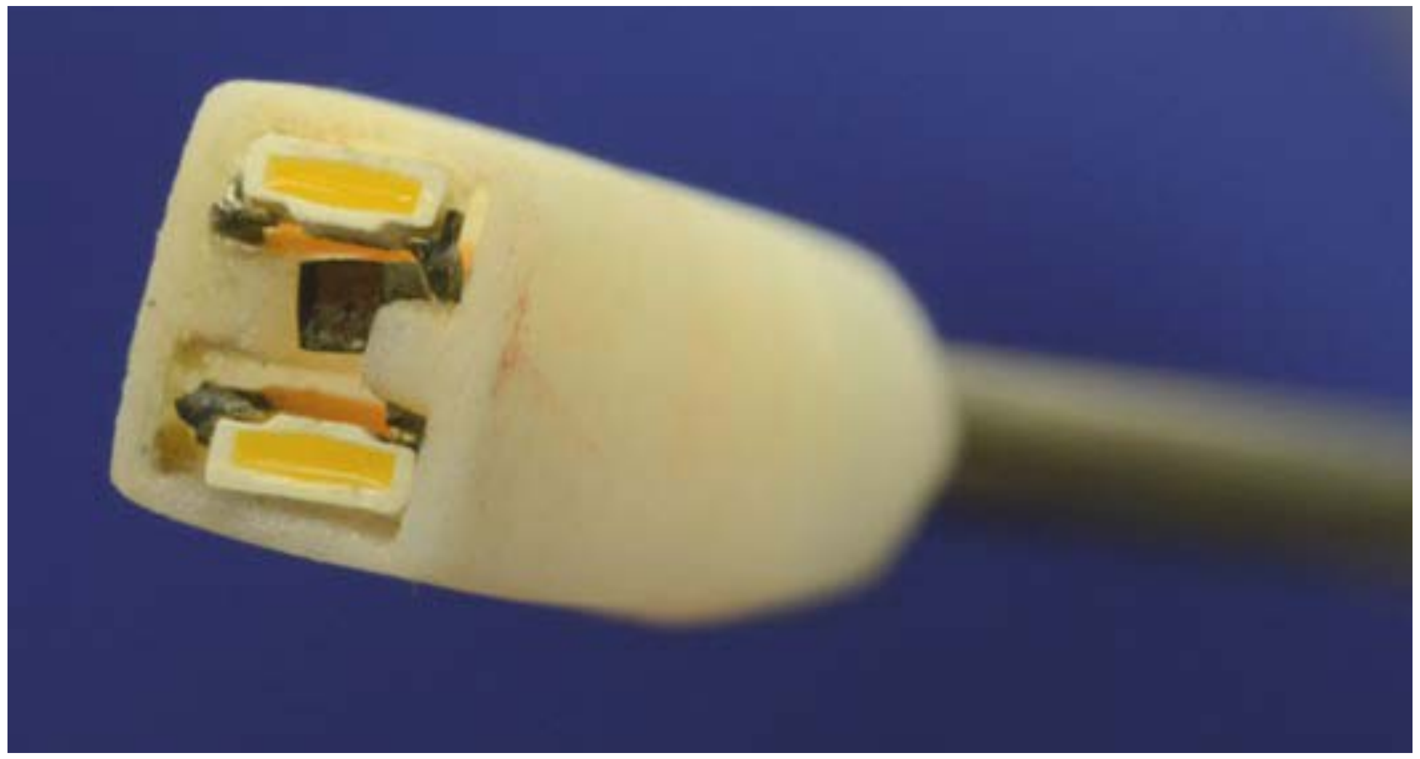
End Effectors

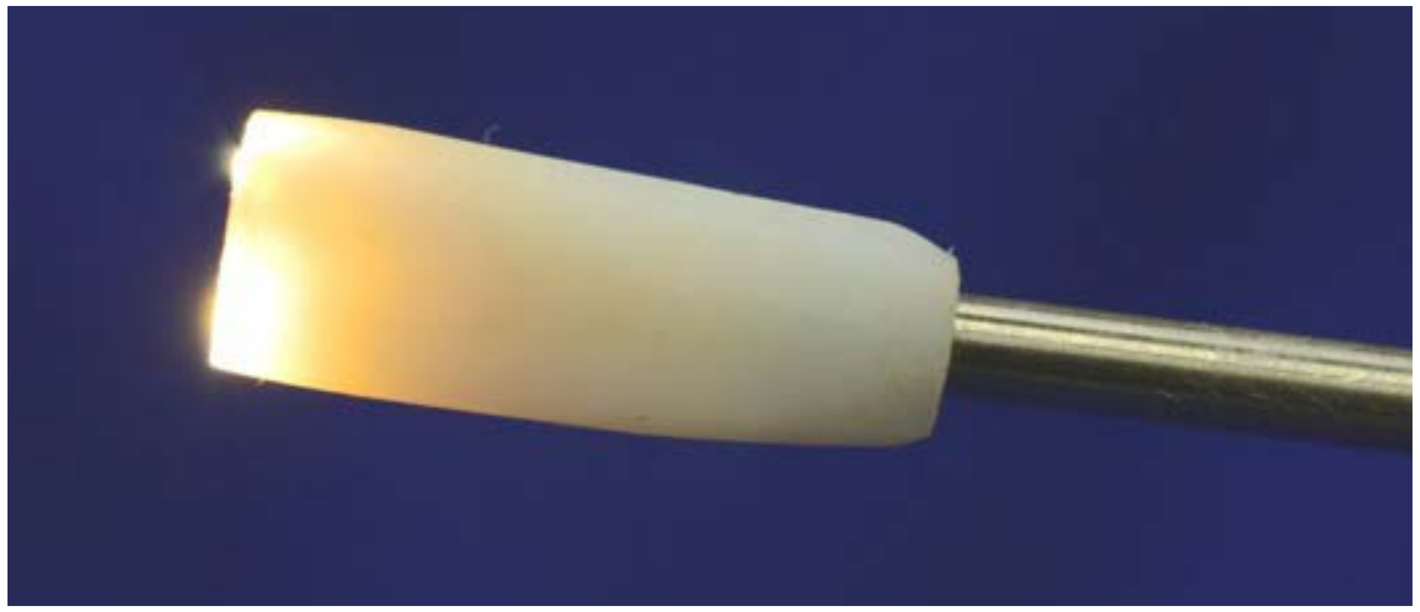


Chip Tip Camera
(Awiba NanEye)

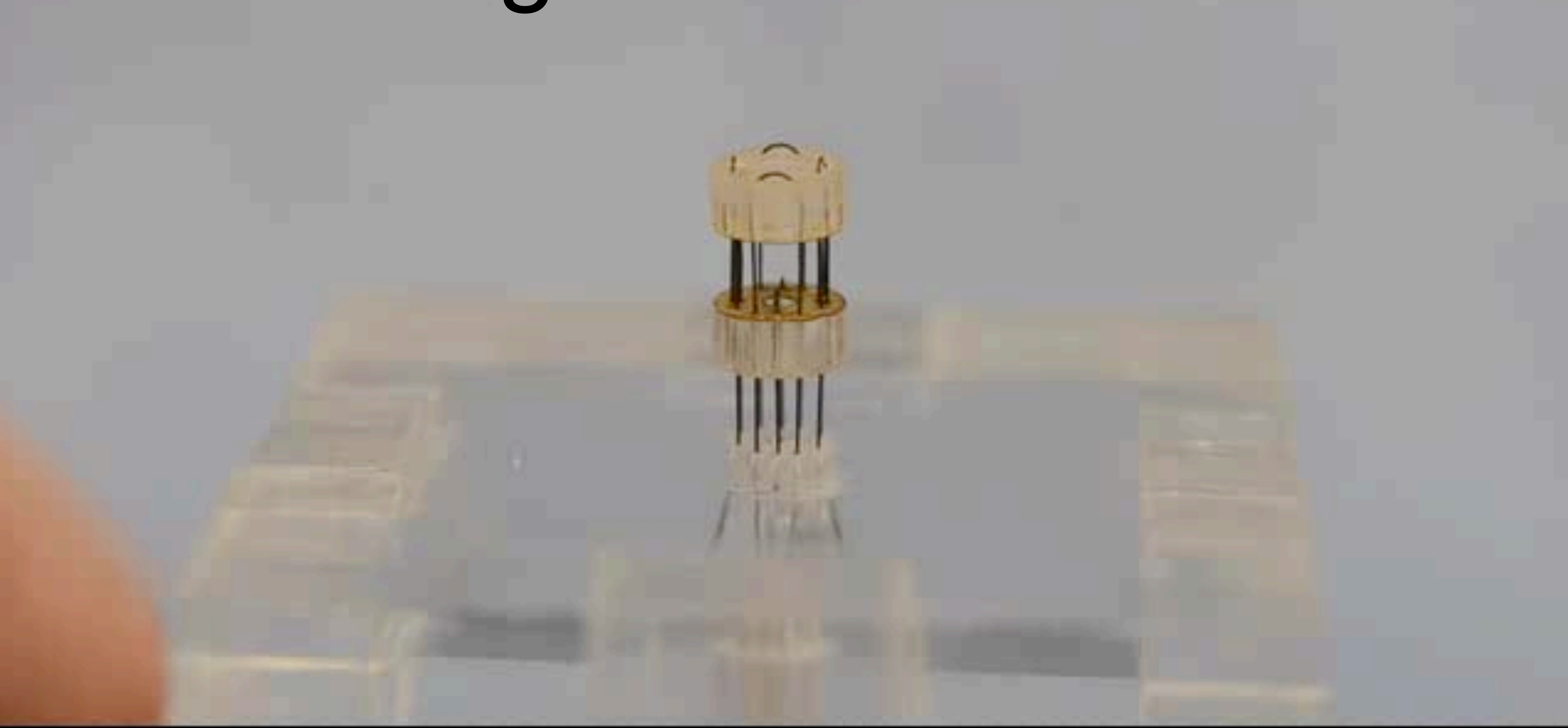


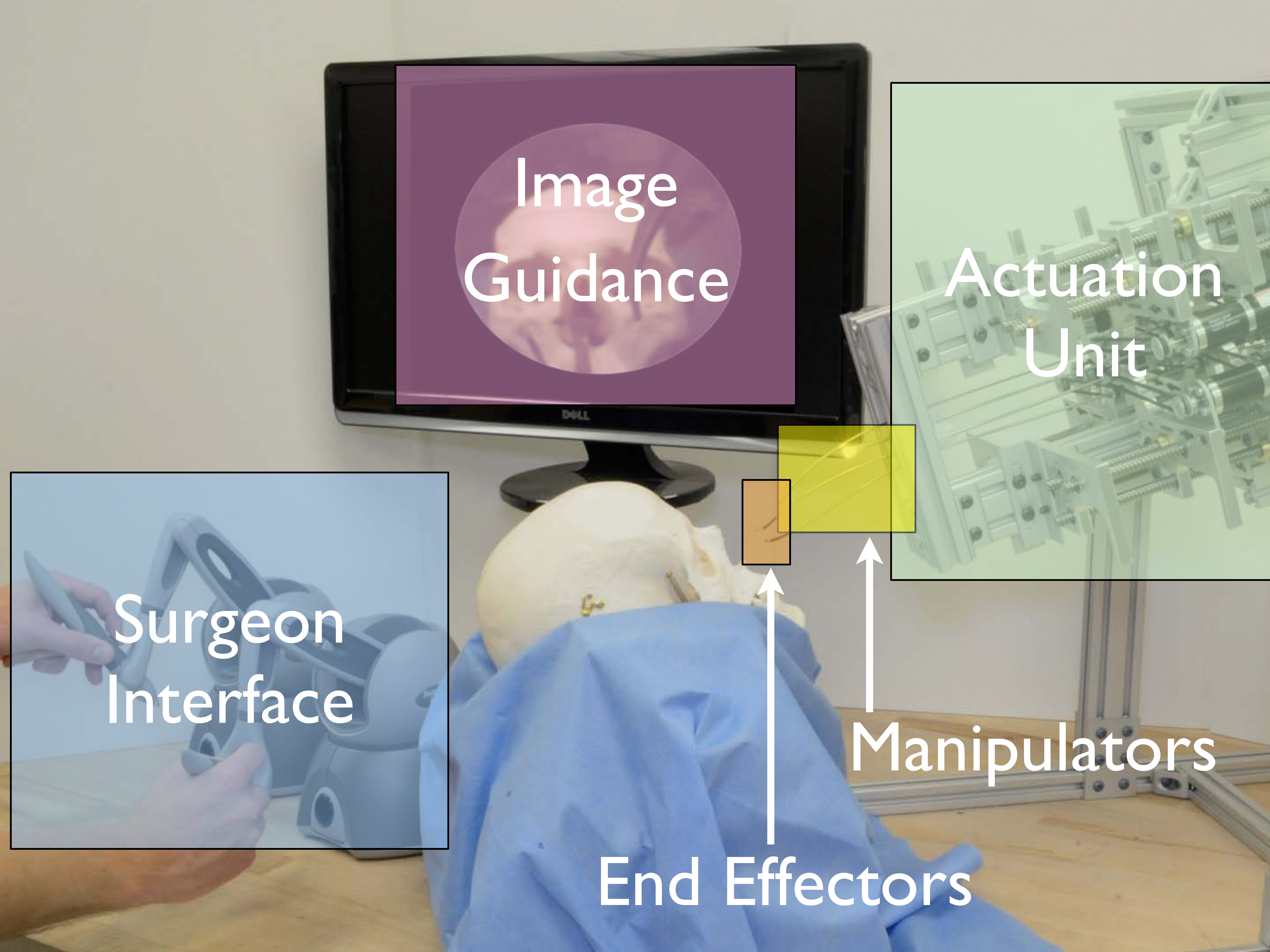






Wrist Designs





Image
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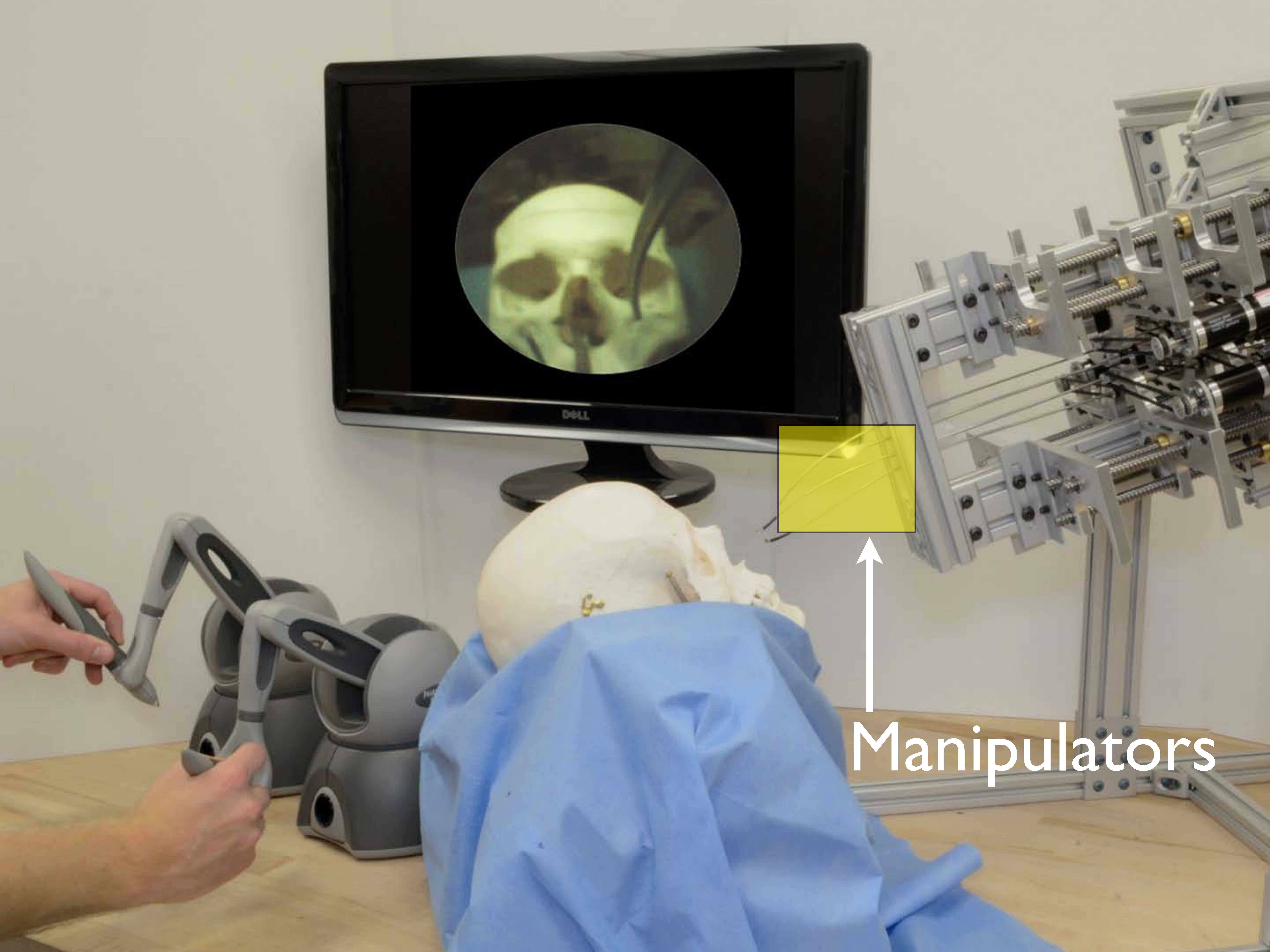
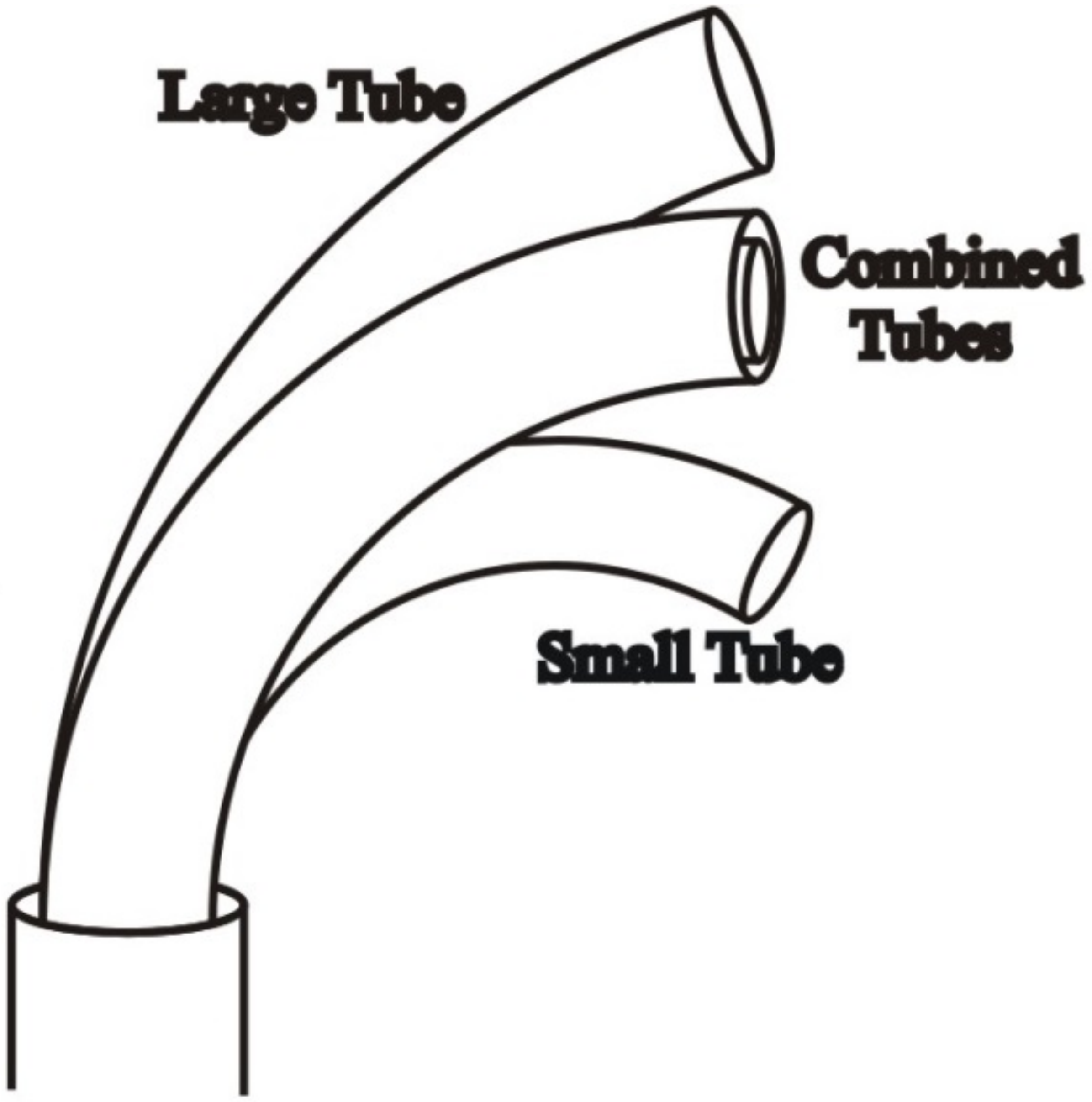
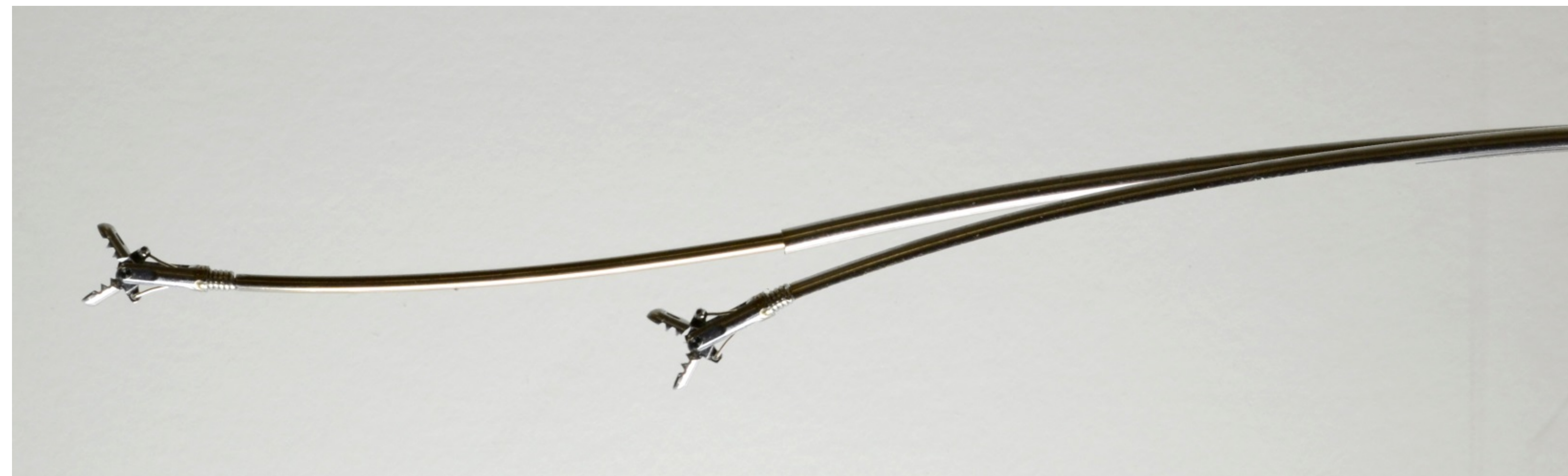

Manipulators

Model Development





Two fully overlapping tubes, pure rotation.

Rigid outer needle, curved inner catheter.

Descriptive Power

Assumptions	Method	Publications
Rigid Outer Tubes	Geometry only	Furusho et al. '05, Daum patent submit '95 award '03
Bending Only	Bernoulli-Euler	Loser '02, Webster '06, Dupont '06
Bending + Trans. Torsion	B-E + Energy	Webster, et al. '06, '08, '09
Bending + General Torsion, General Tube Shapes	Energy Methods/ Cosserat Rods	Rucker and Webster et al. '08, '09, '10, Dupont, et al. '09, '10
External Loads, Single Rod	Cosserat Rods	Dupont et al. TRO '10
External Loads, Free Tubes	Cosserat Rods	Rucker, Jones, and Webster TRO '10

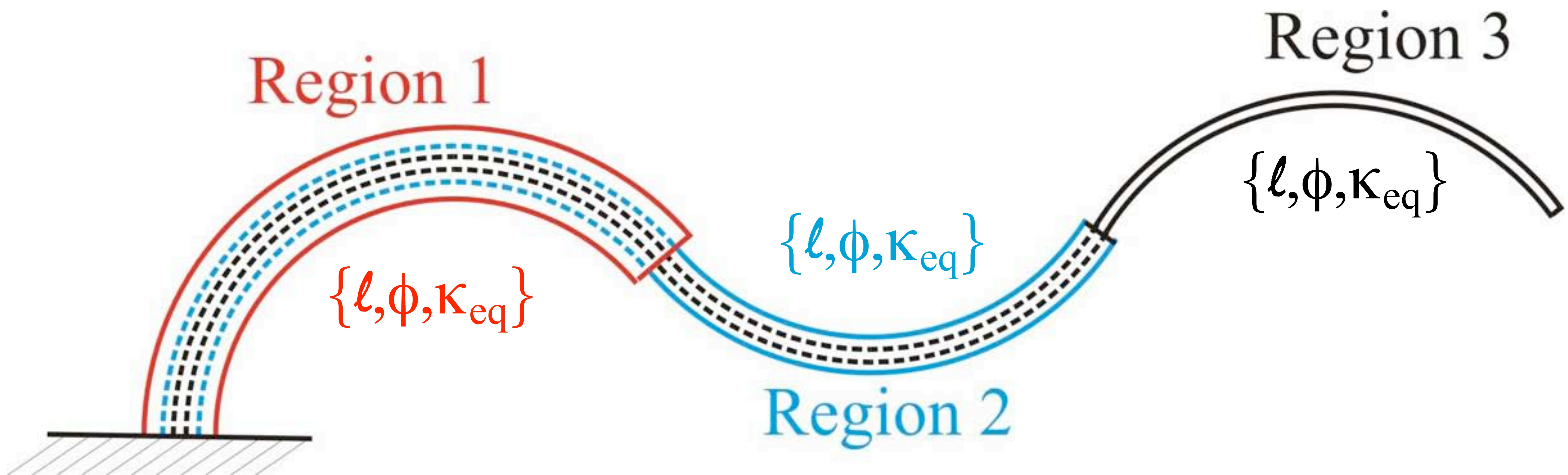
Complexity

Bifurcations? (Webster '09)

Friction? (Dupont '11)

Tube Tolerances? (Webster '10)

Kinematics for Cannula

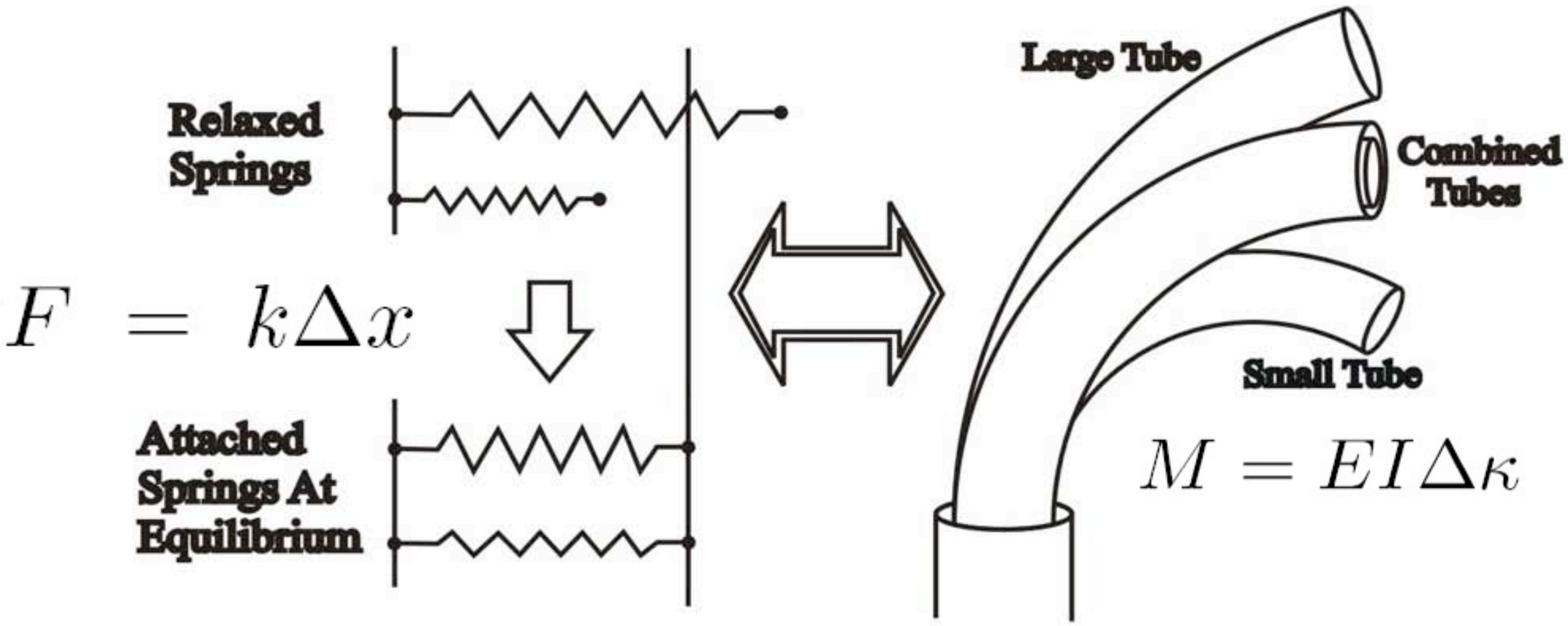


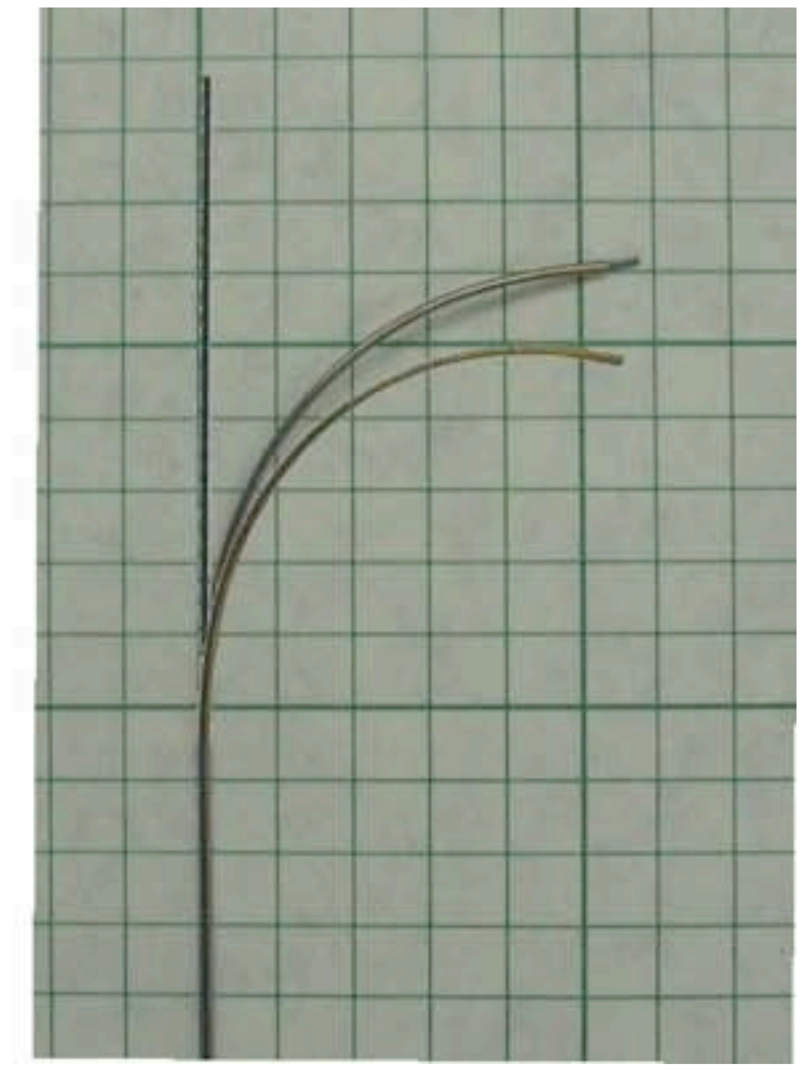
Each region is a curved robot “link”
Goals:

- describe curve shape (Forward Kinematics)
- describe velocity of any point (Differential Kinematics)

Modeling Goal: Obtain “Arc Parameters”

One Link: Planar Case



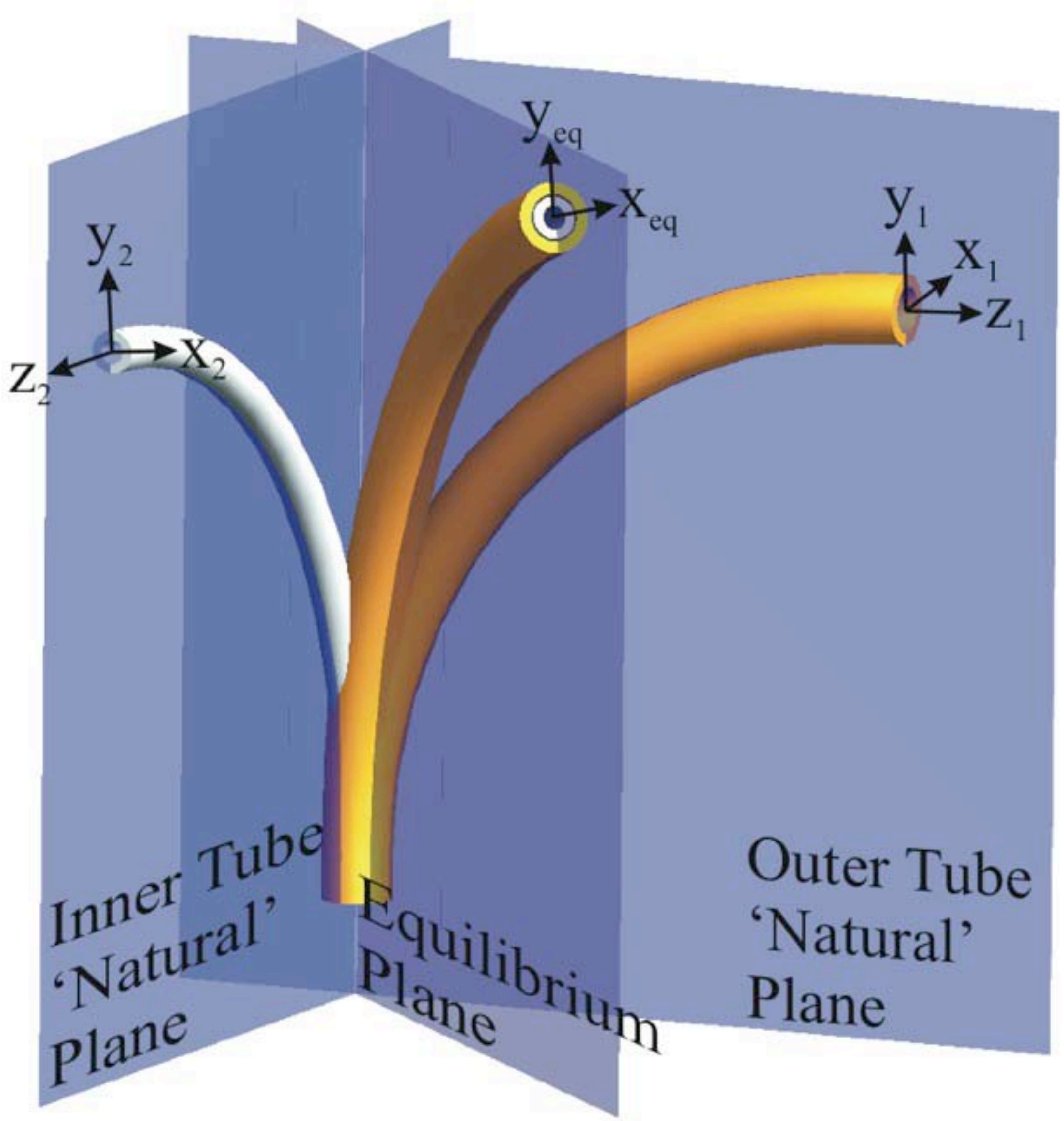


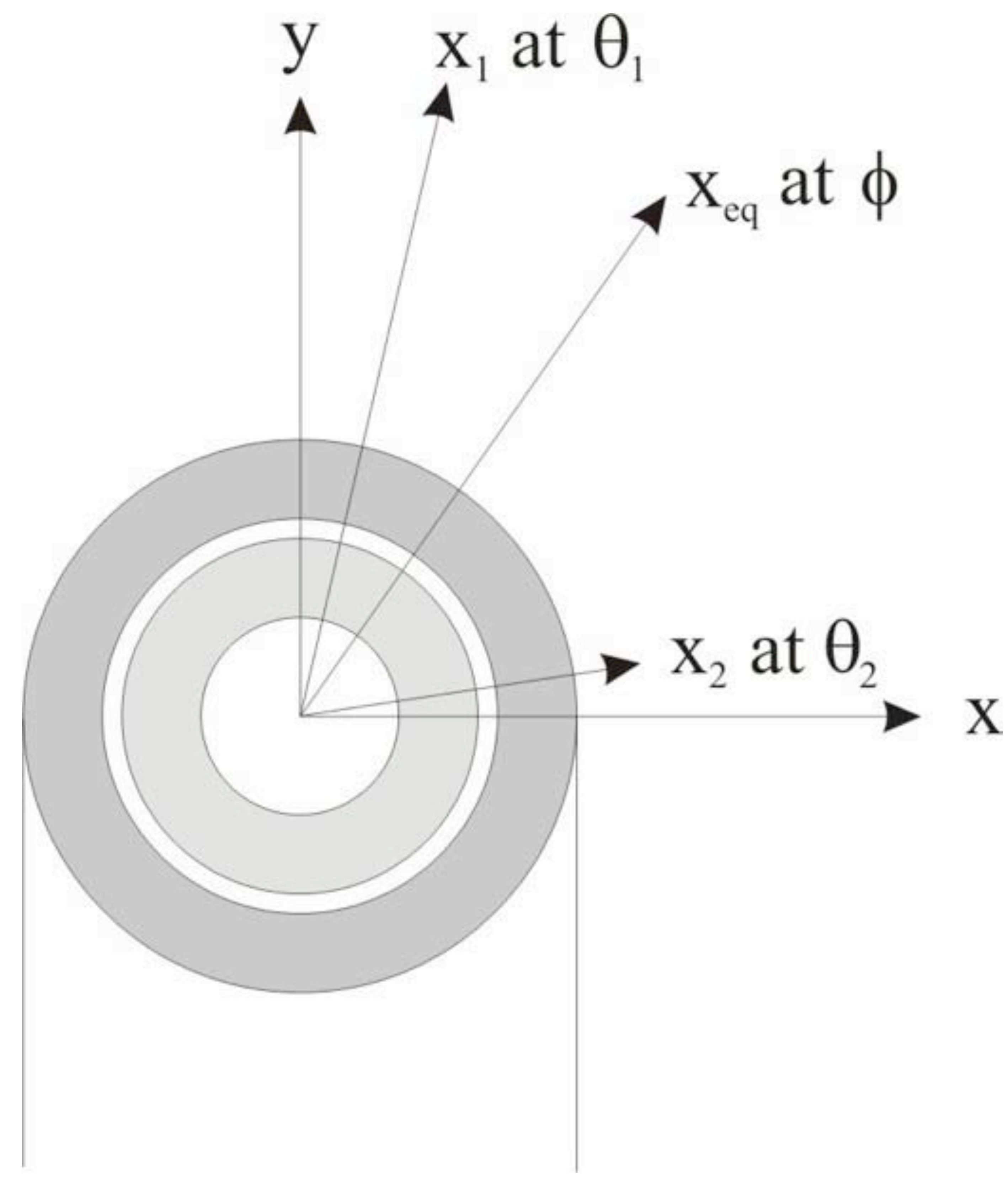
Tubes Analogous to Springs In Parallel

Tube			Wire		Combined	
ID (mm)	OD (mm)	κ (1/mm)	OD (mm)	κ (1/mm)	r meas (mm)	r pred (mm)
0.622	0.800	0.044	0.43	0.0	26.0	25.5
0.965	1.27	0.020	0.8	0.0	62.5	61.2
1.47	1.78	0.021	1.2954	0.0	75.5	72.8
2.01	2.39	0.028	1.6002	0.0	49.8	50.5

VERIFICATION OF BERNOULLI-EULER BASED BEAM MECHANICS MODEL.

$$\kappa_{eq} = \frac{\sum_{i=1}^{n} E_i I_i \kappa_i}{\sum_{i=1}^{n} E_i I_i}$$

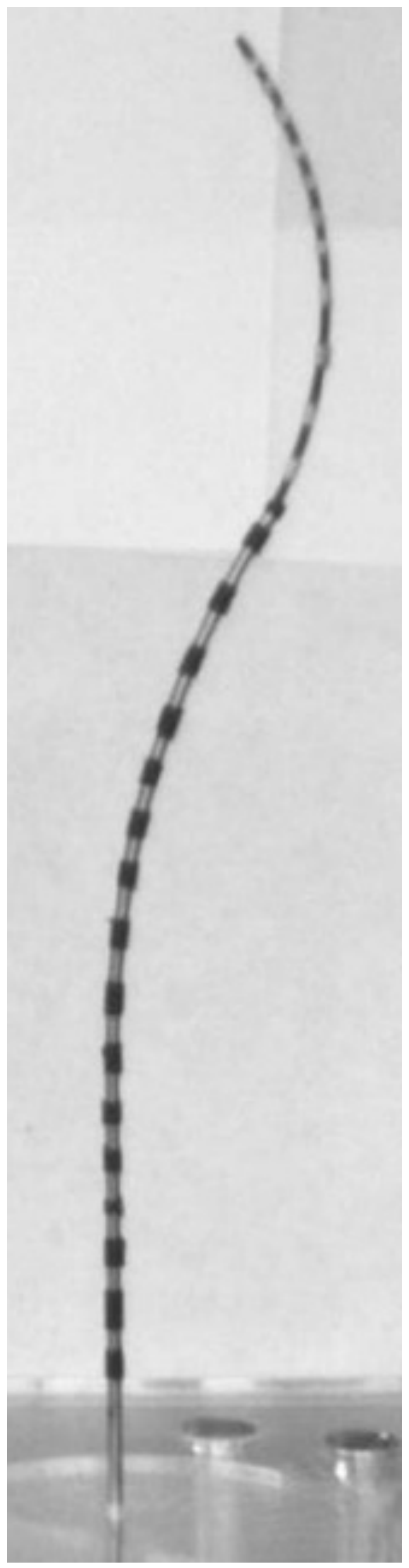


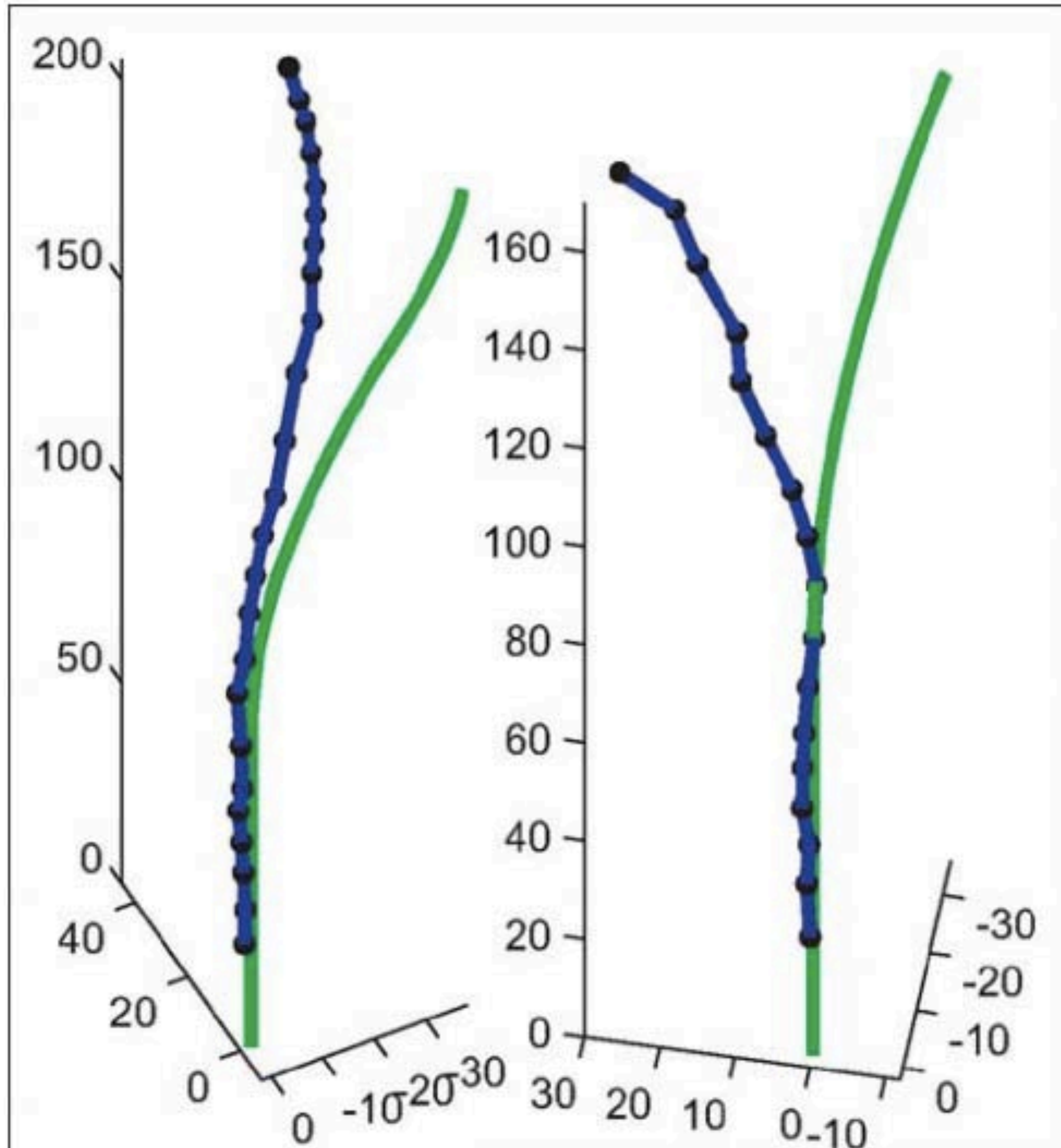


$$k_x = \frac{\sum_{i=1}^{n} E_i I_i \kappa_i \cos(\theta_i)}{\sum_{i=1}^{n} E_i I_i} \qquad k_y = \frac{\sum_{i=1}^{n} E_i I_i \kappa_i \sin(\theta_i)}{\sum_{i=1}^{n} E_i I_i}$$

$$\kappa_{eq} = \sqrt{\kappa_x^2 + \kappa_y^2} \qquad \phi = \tan^{-1}\left(\frac{\kappa_x}{\kappa_y}\right)$$

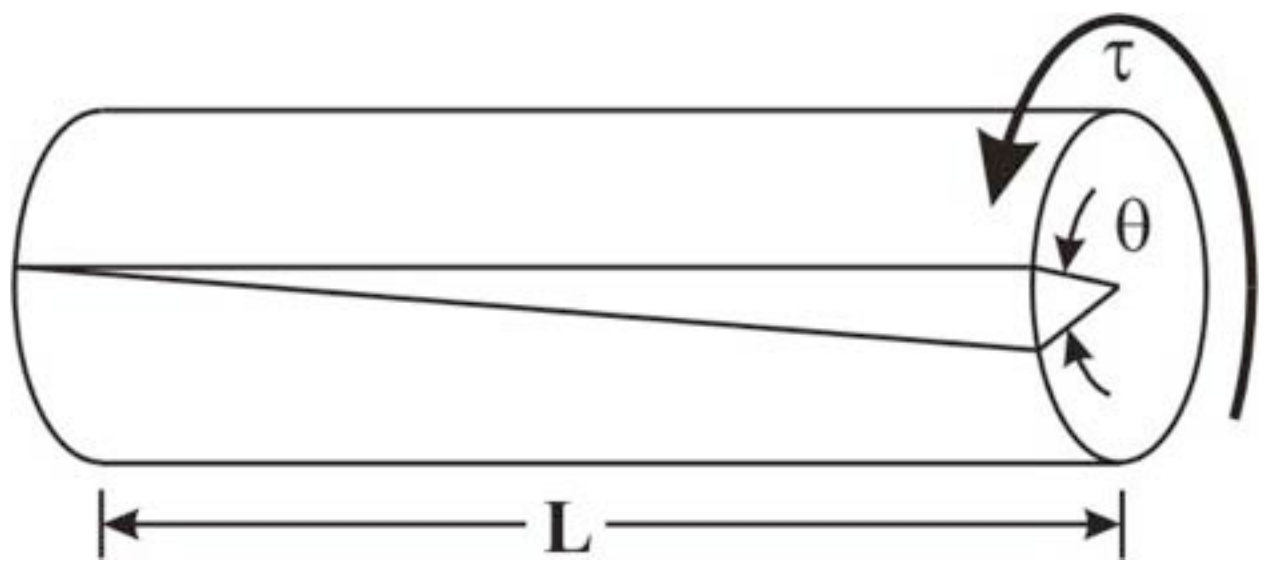
Worked Terribly!



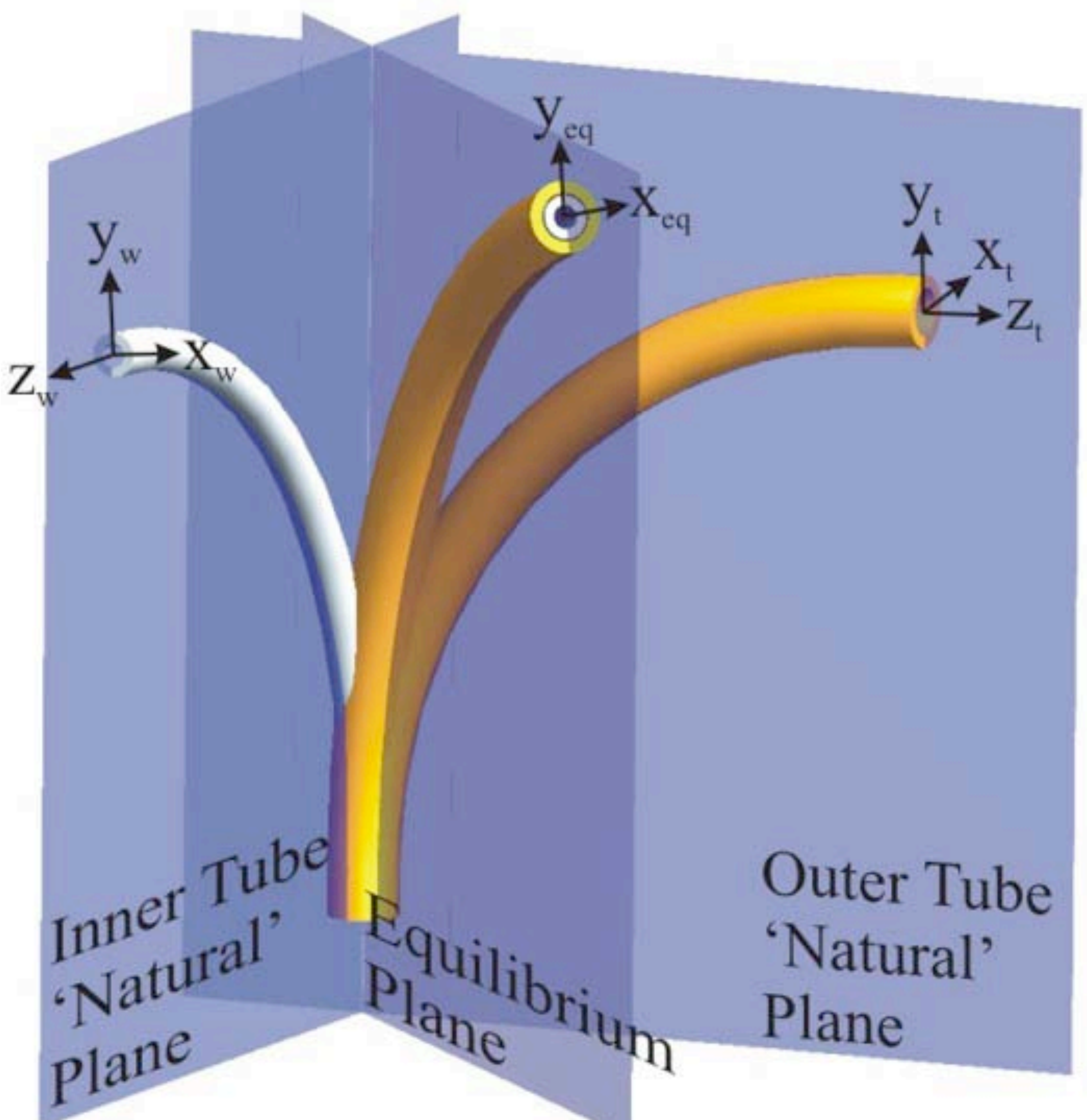


Torsionally Rigid Model

Solution: Model Torsion in the Straight Transmission

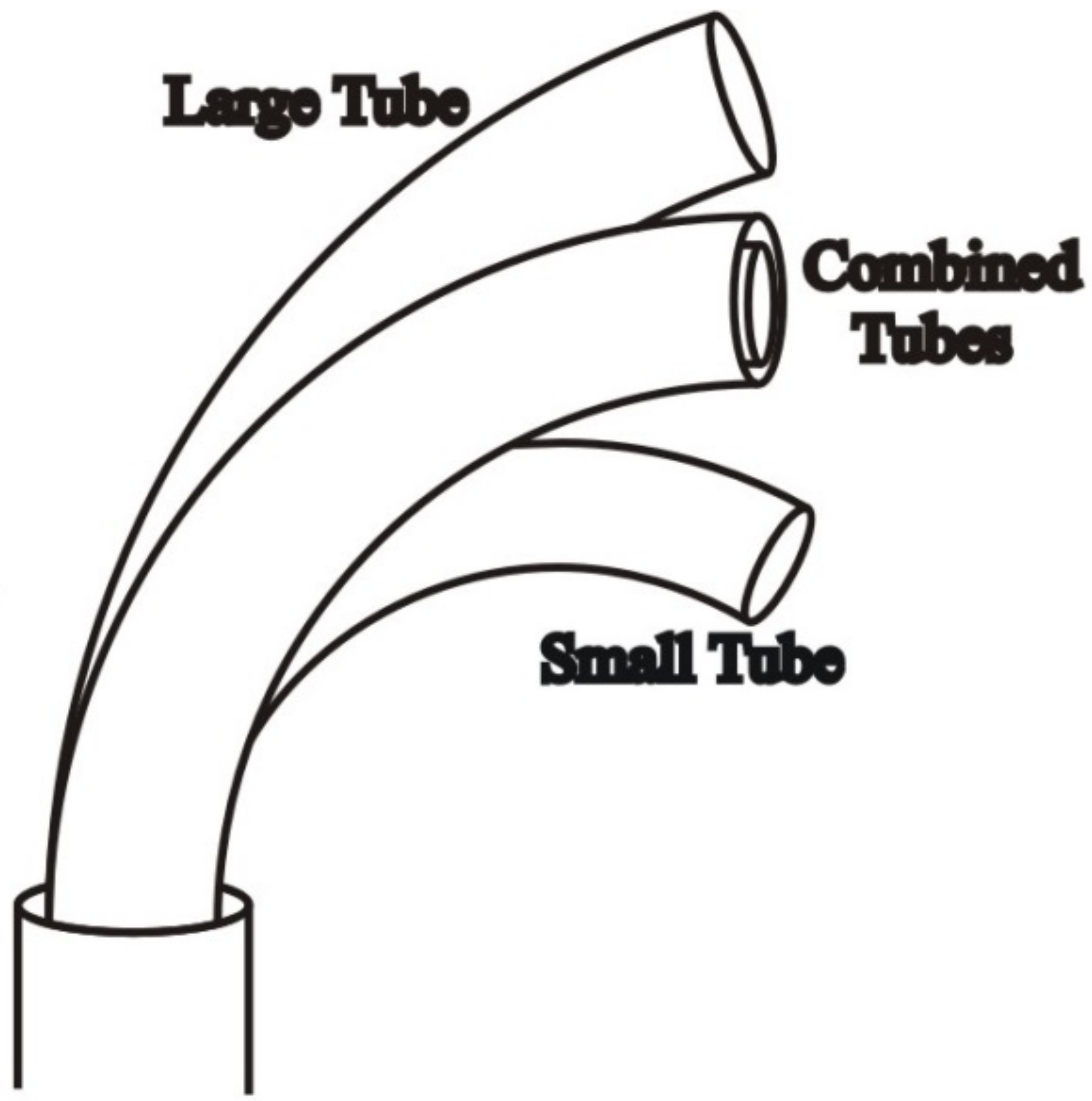


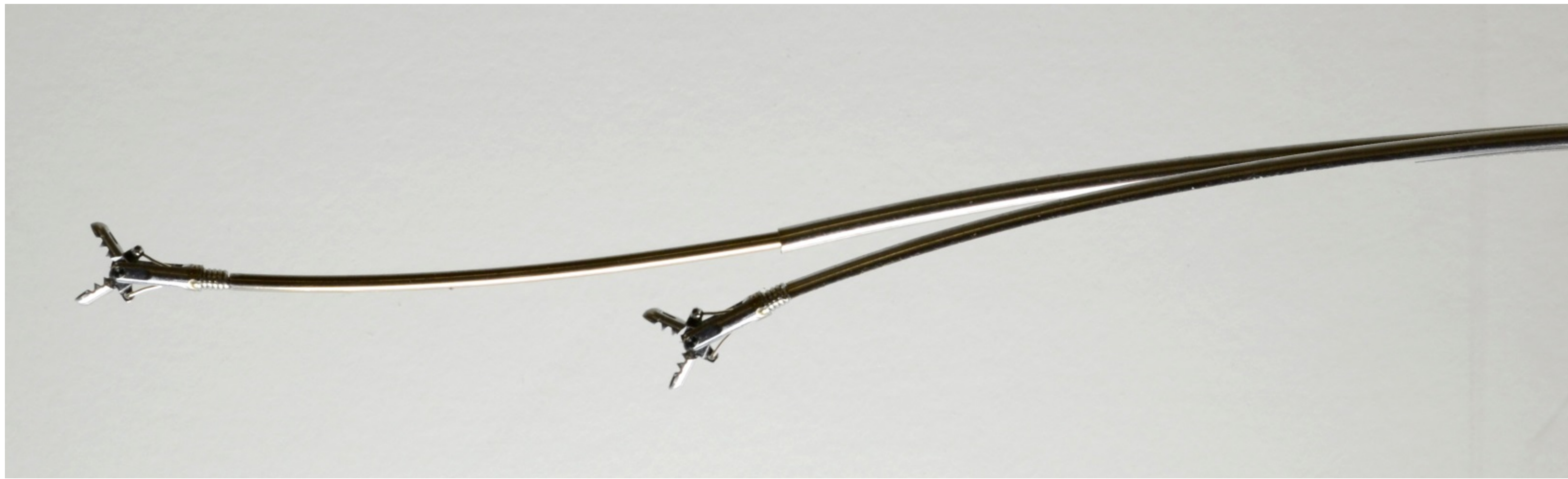
$$U = \int_0^L \frac{\tau^2}{2GJ}\,ds = \frac{GJ}{2L}\Delta\theta^2$$



$$U(\theta) = \underbrace{\sum_{i=1}^{n} \frac{G_i J_i}{2L_i}(\alpha_i - \theta_{i,1})^2}_{\text{transmission torsion}} + \underbrace{\sum_{j=1}^{m}\sum_{i=1}^{n} \frac{E_i I_i \ell_j}{2}(\kappa_{x,j} - \kappa_i \cos(\theta_{i,j}))^2}_{x \text{ direction bending}} + \underbrace{\sum_{j=1}^{m}\sum_{i=1}^{n} \frac{E_i I_i \ell_j}{2}(\kappa_{y,j} - \kappa_i \sin(\theta_{i,j}))^2}_{y \text{ direction bending}}$$

Model Development





The Sweet Spot?

Descriptive Power

Assumptions	Method	Publications
Rigid Outer Tubes	Geometry only	Furusho et al. '05, Daum patent submit '95 award '03
Bending Only	Bernoulli-Euler	Loser '02, Webster '06, Dupont '06
Bending + Trans. Torsion	B-E + Energy	Webster, et al. '06, '08, '09
Bending + General Torsion, General Tube Shapes	Energy Methods/ Cosserat Rods	Rucker and Webster et al. '08, '09, '10, Dupont, et al. '09, '10
External Loads, Single Rod	Cosserat Rods	Dupont et al. TRO '10
External Loads, Free Tubes	Cosserat Rods	Rucker, Jones, and Webster TRO '10

Complexity

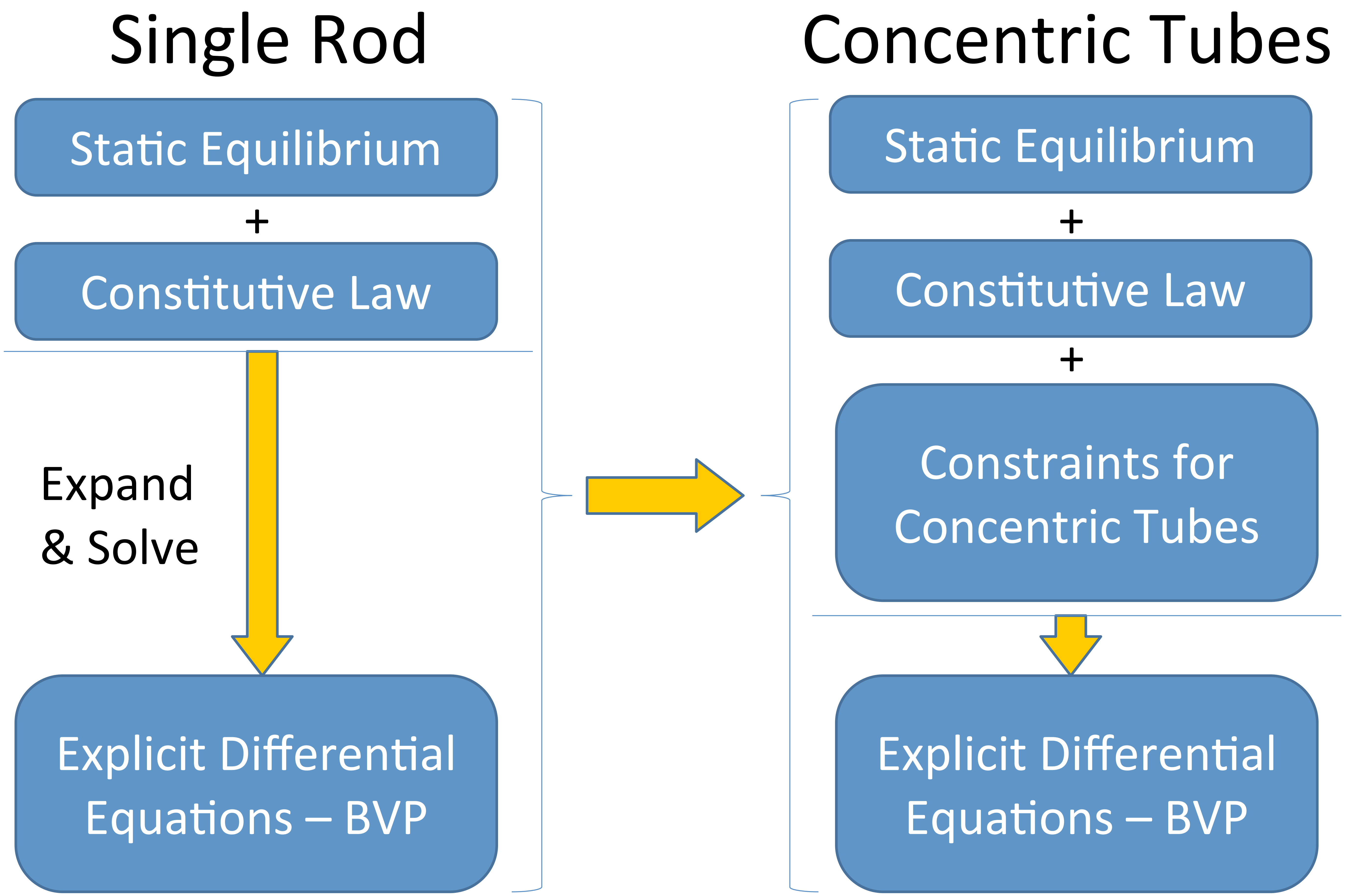
Bifurcations? (Webster '09)

Friction? (Dupont '11)

Tube Tolerances? (Webster '10)

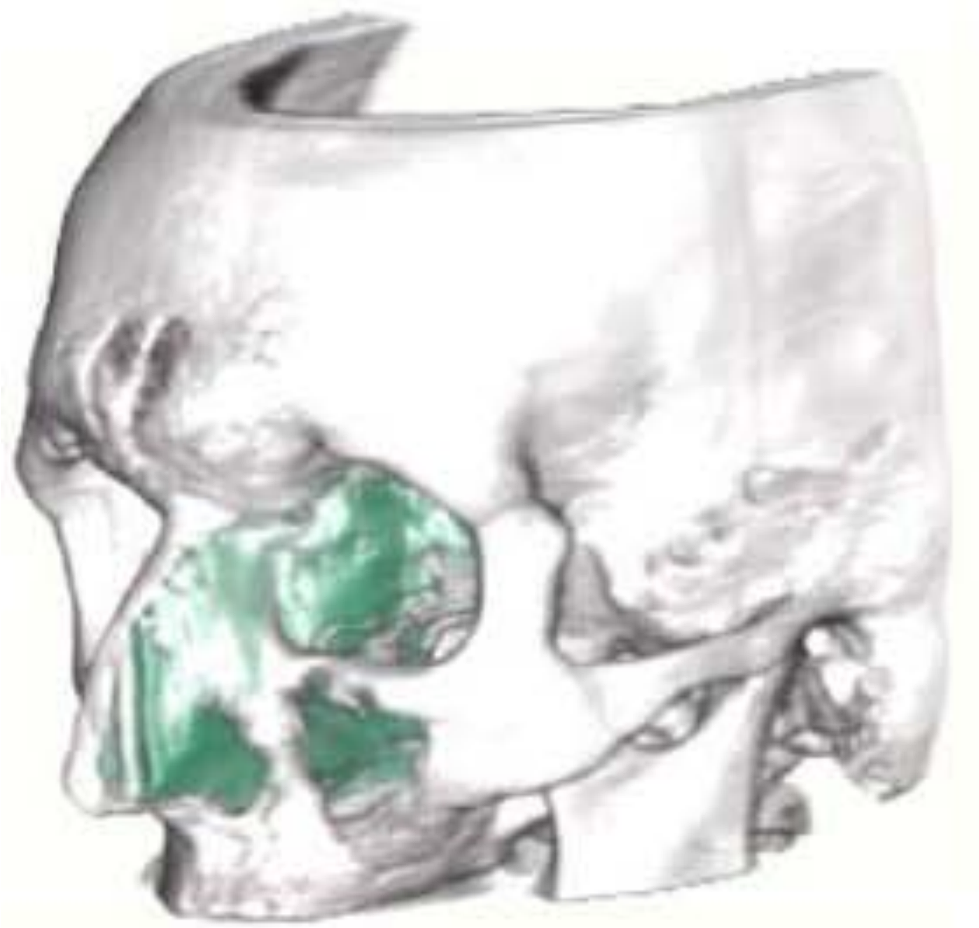
Modeling: General Tube Shapes, External Loads

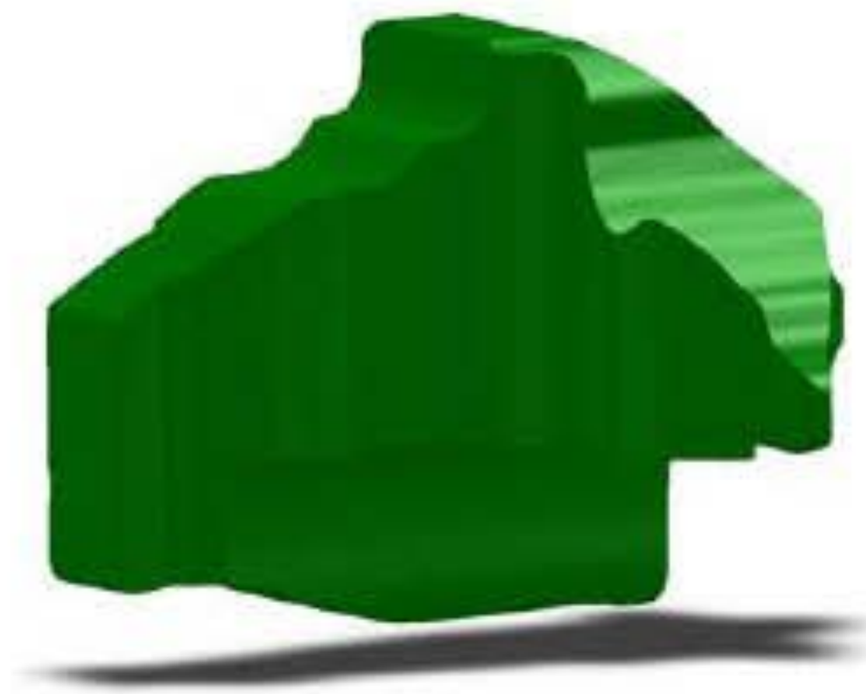
Stuart S. Antman. Nonlinear Problems of Elasticity. Springer Science, 2nd edition, 2005.

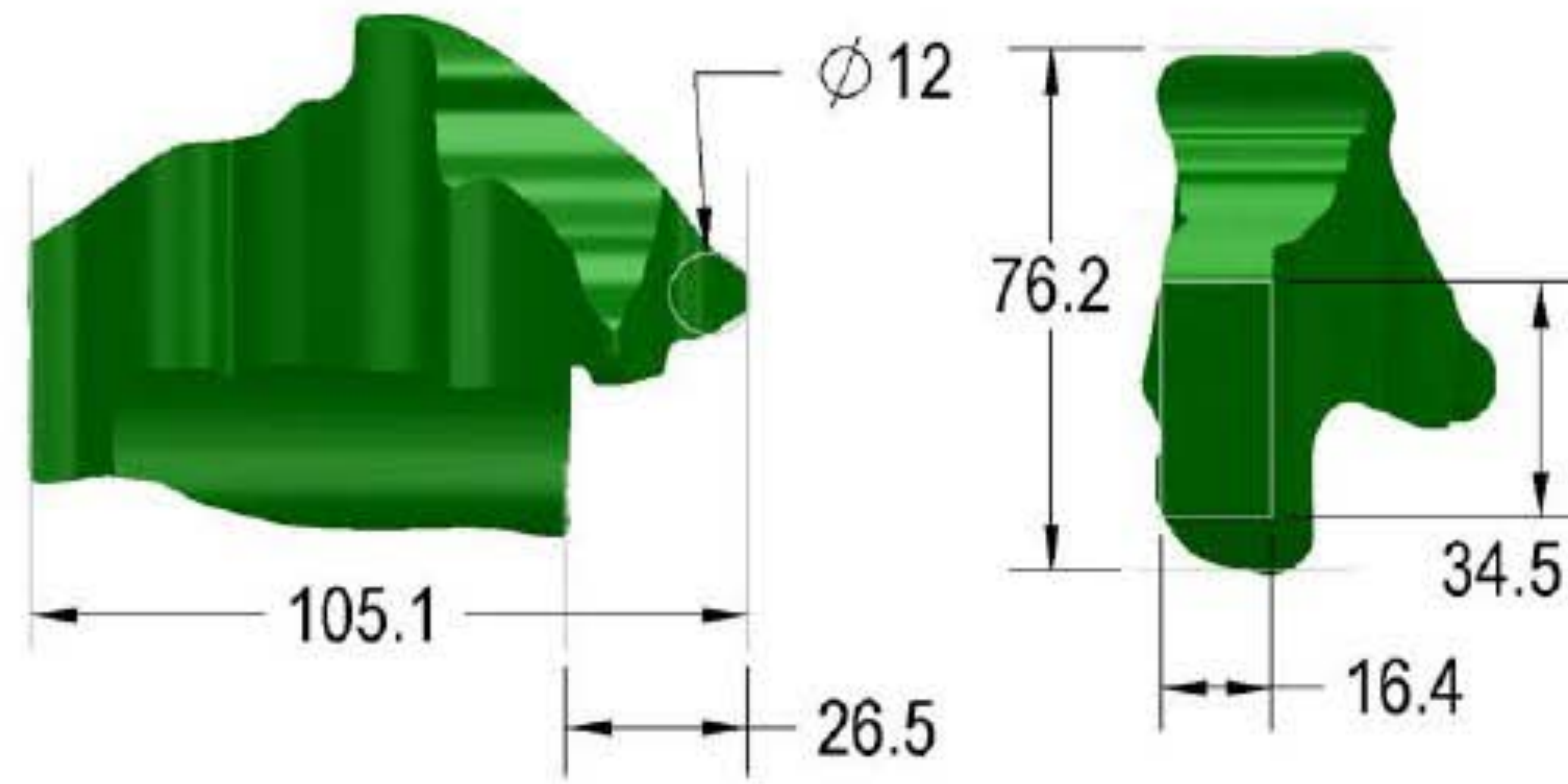


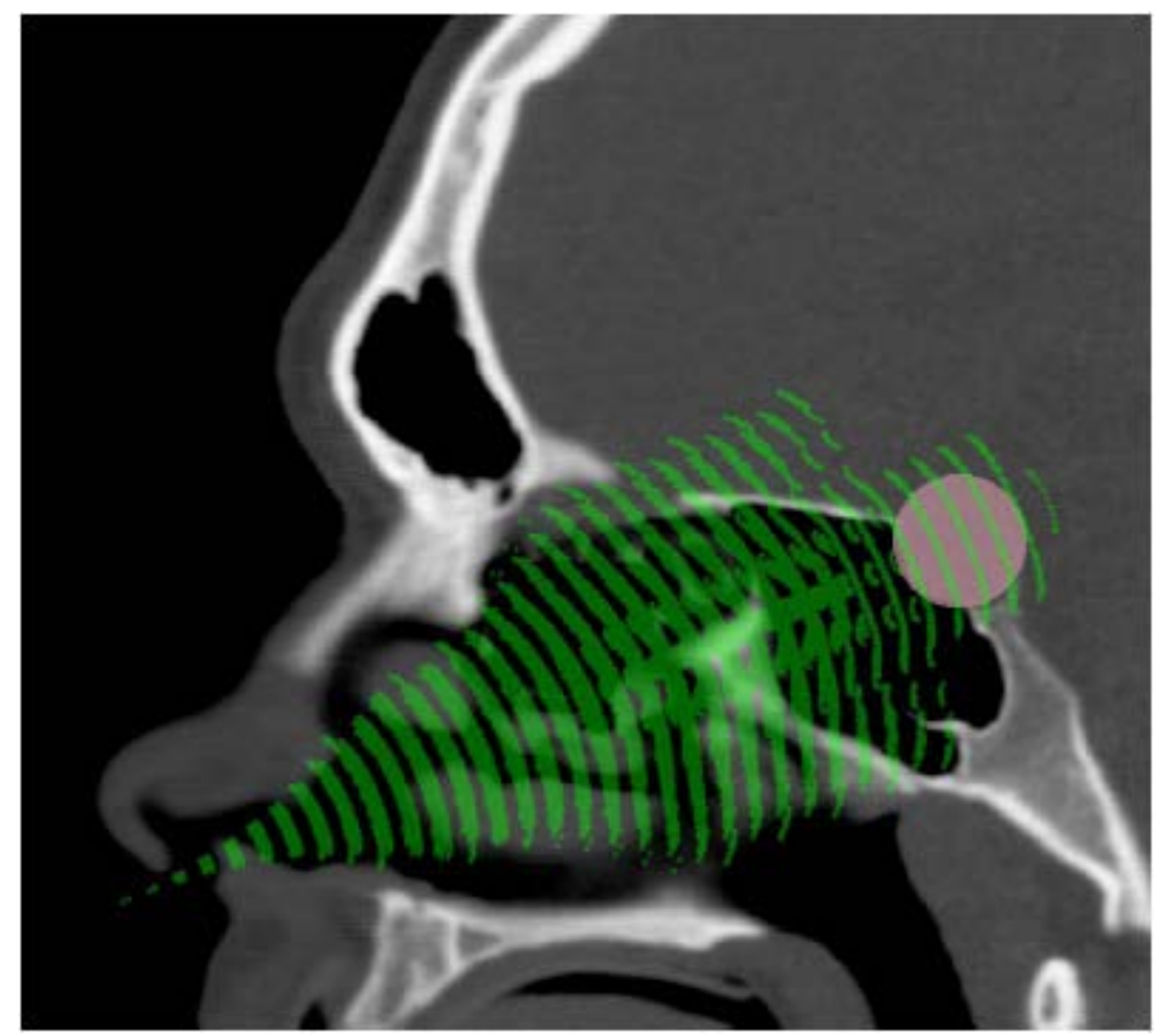
Rucker, Jones, and Webster, "A Geometrically Exact Model for Externally Loaded Concentric Tube Continuum Robots," TRO 2010.

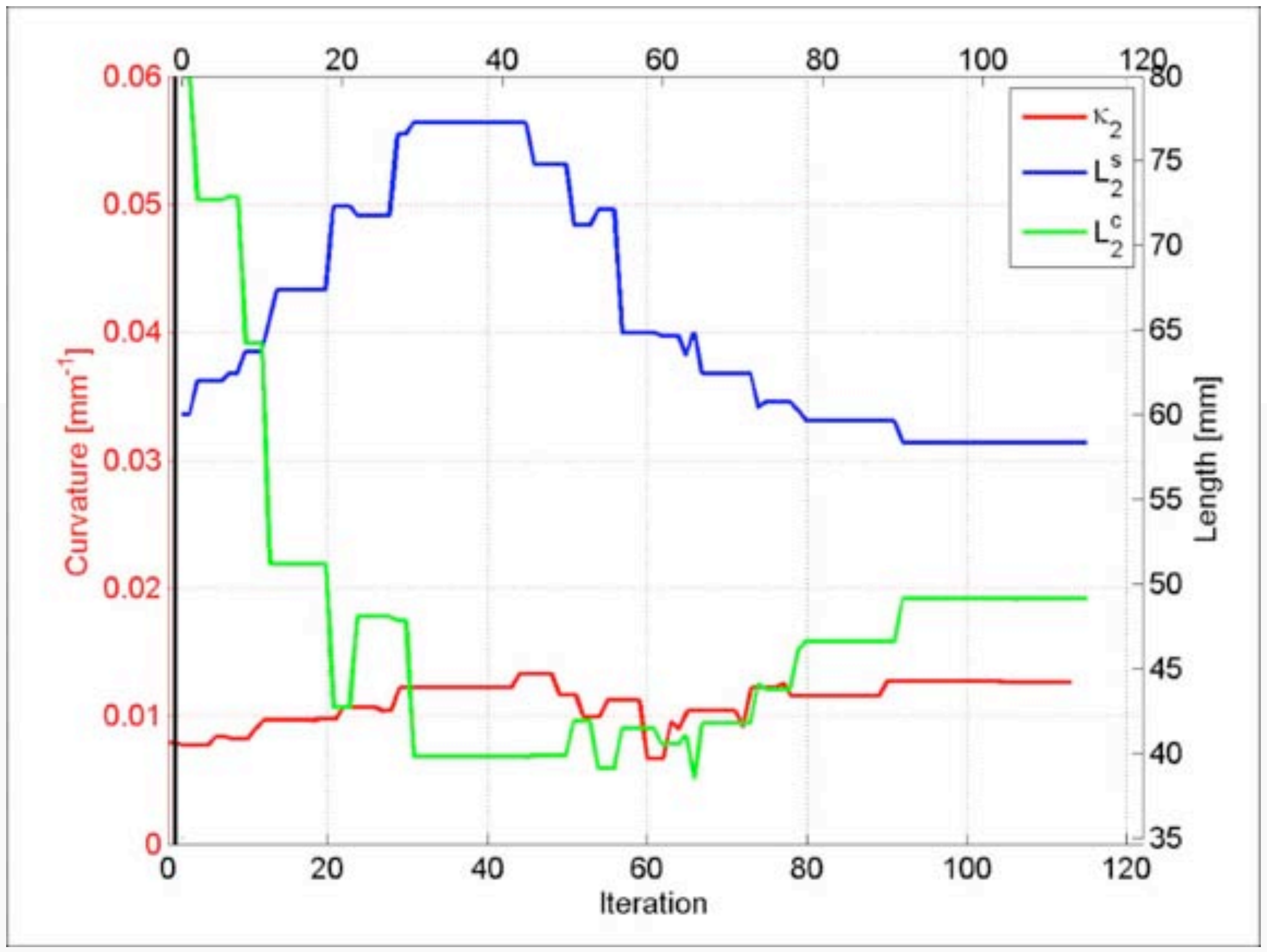
Tube Design

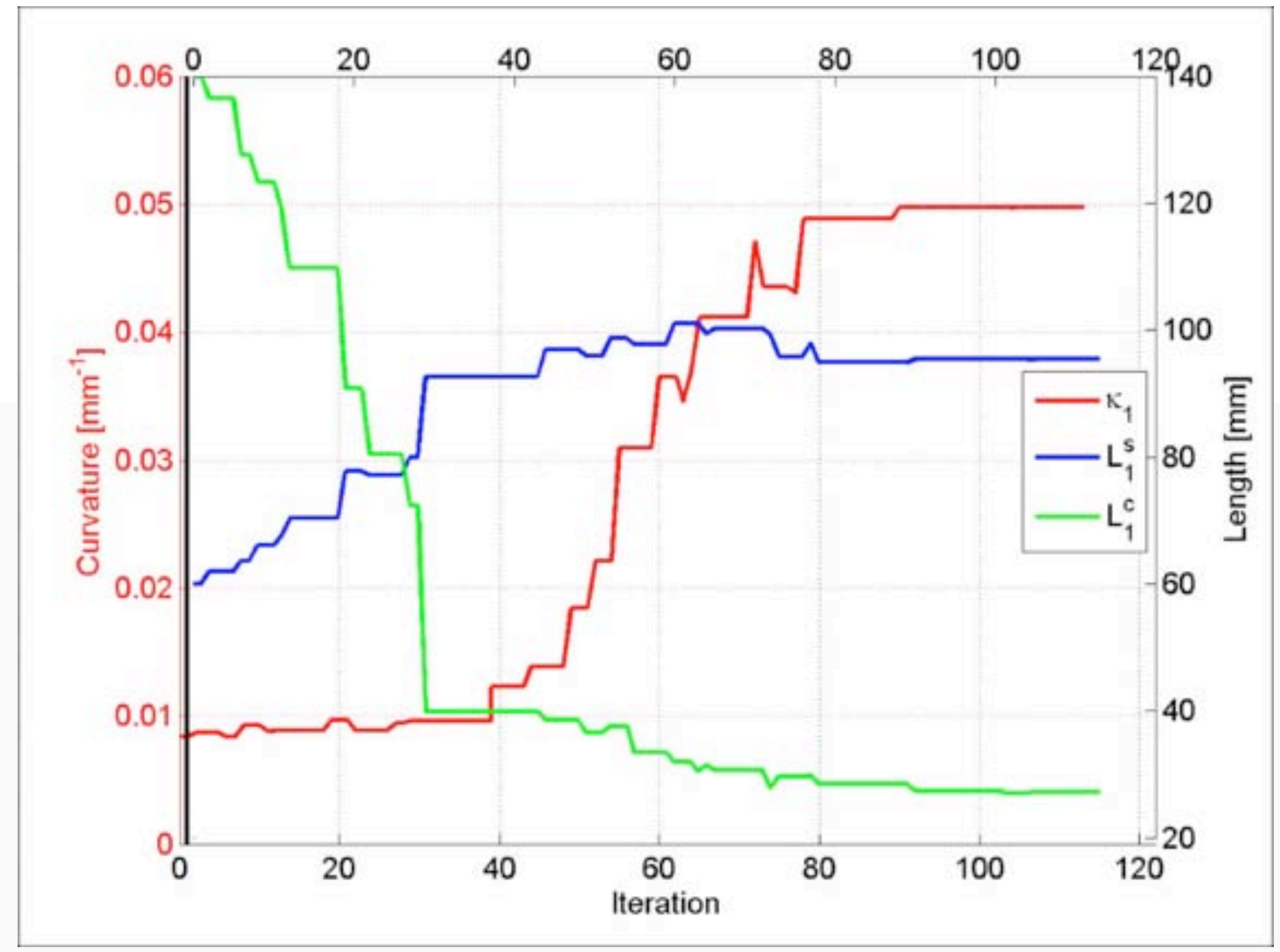


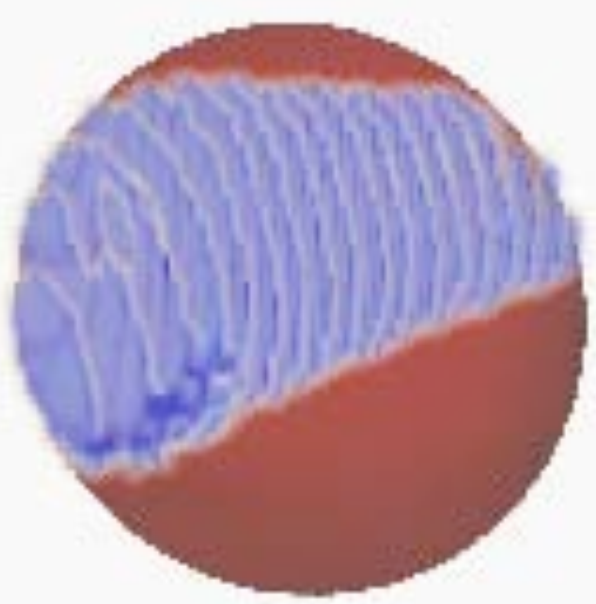


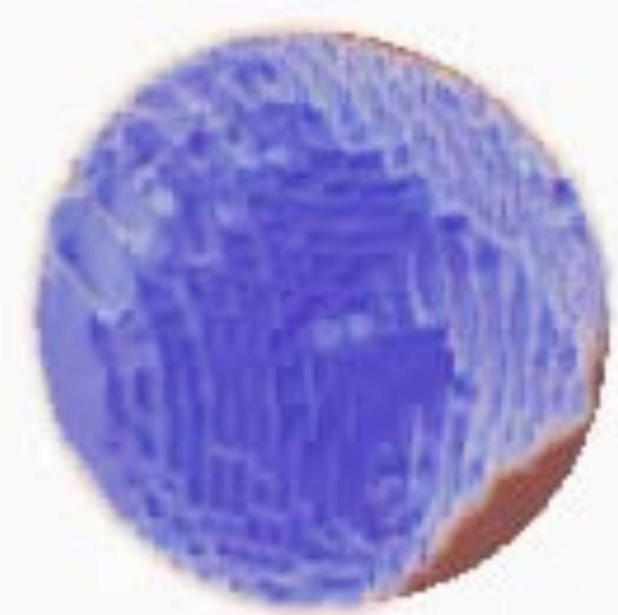




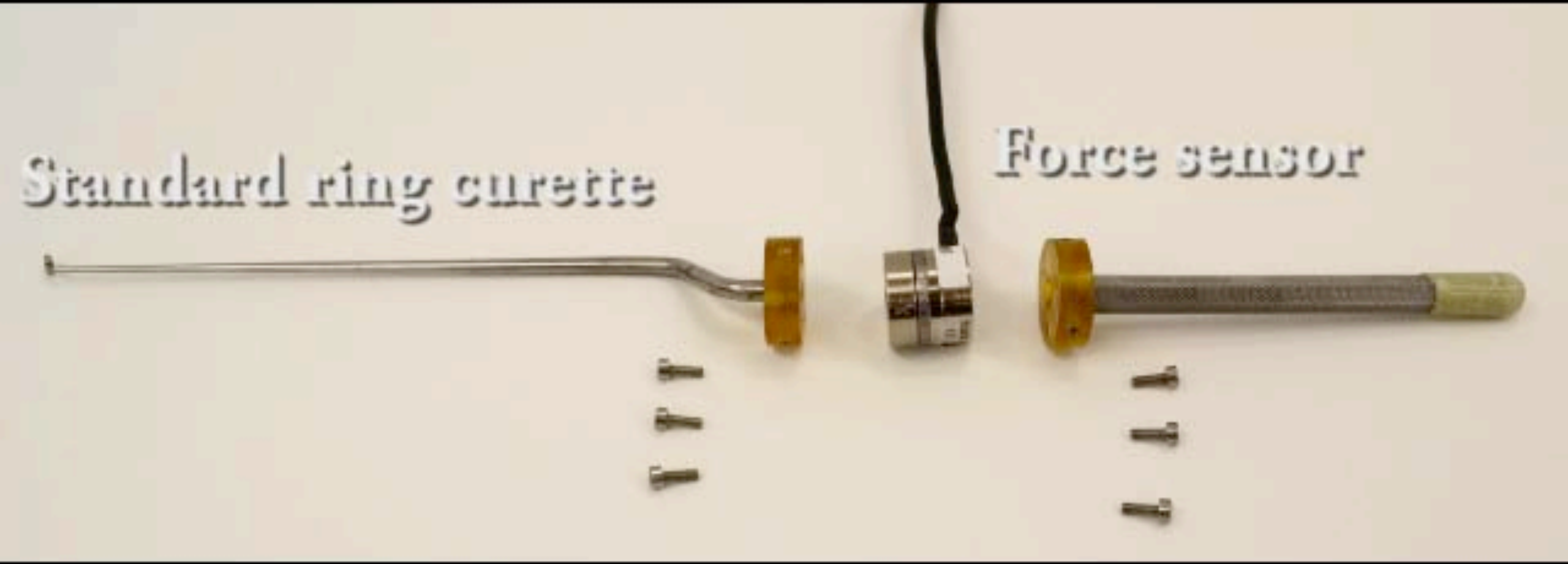






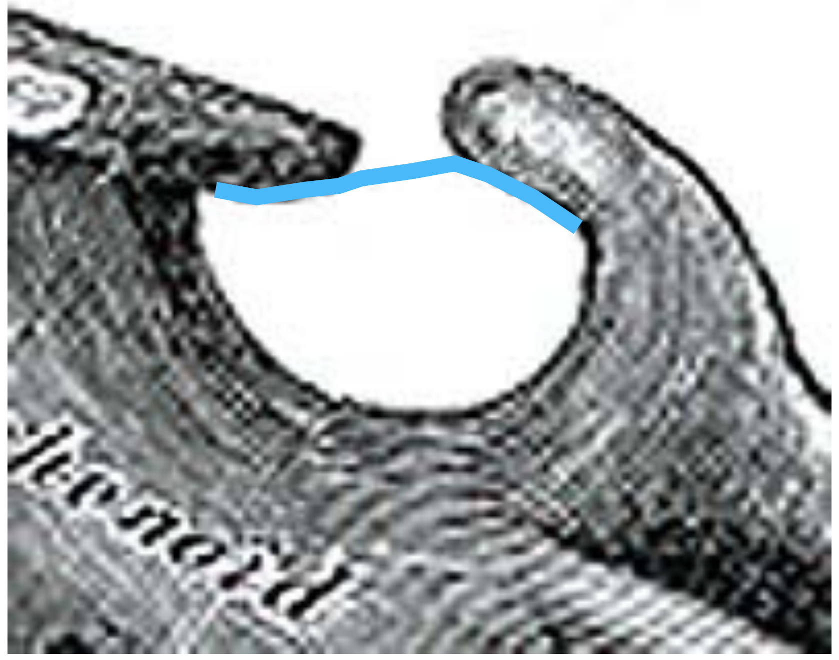


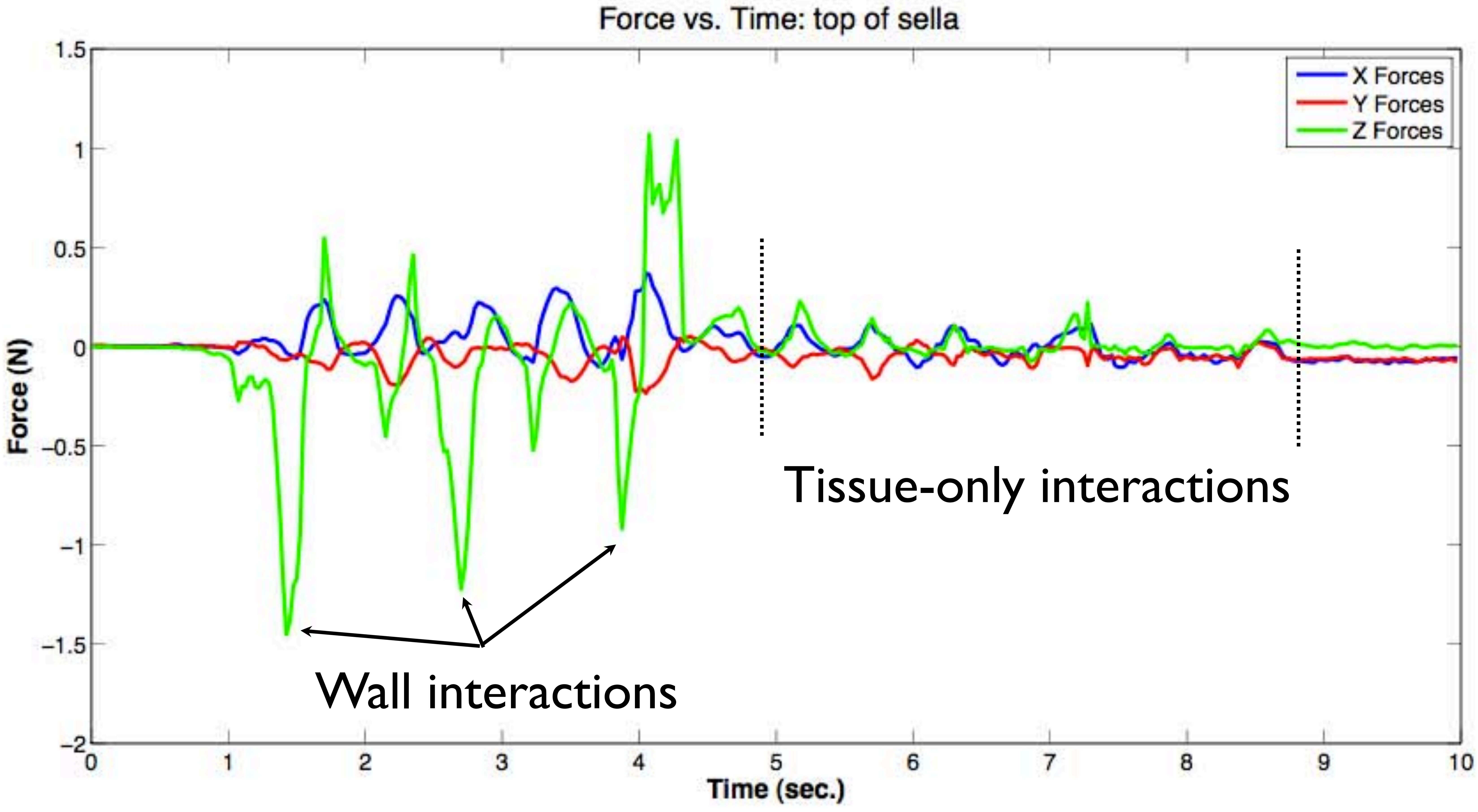
Burgner, Gilbert, and Webster, "On the Computational Design of Concentric Tube Robots: Incorporating Volume-Based Objectives" ICRA 2013, Best Medical Robotics Paper Finalist


Standard ring curette
Force sensor


Codman 85 80-1347

Top of the sella turcia





Bekeny, Swaney, Webster, Russell, Weaver, "Forces Applied at the Skull Base During Transnasal Endoscopic Transsphenoidal Pituitary Tumor Excision," J Neurol. Surg. Part B: Skull Base. (In Press).

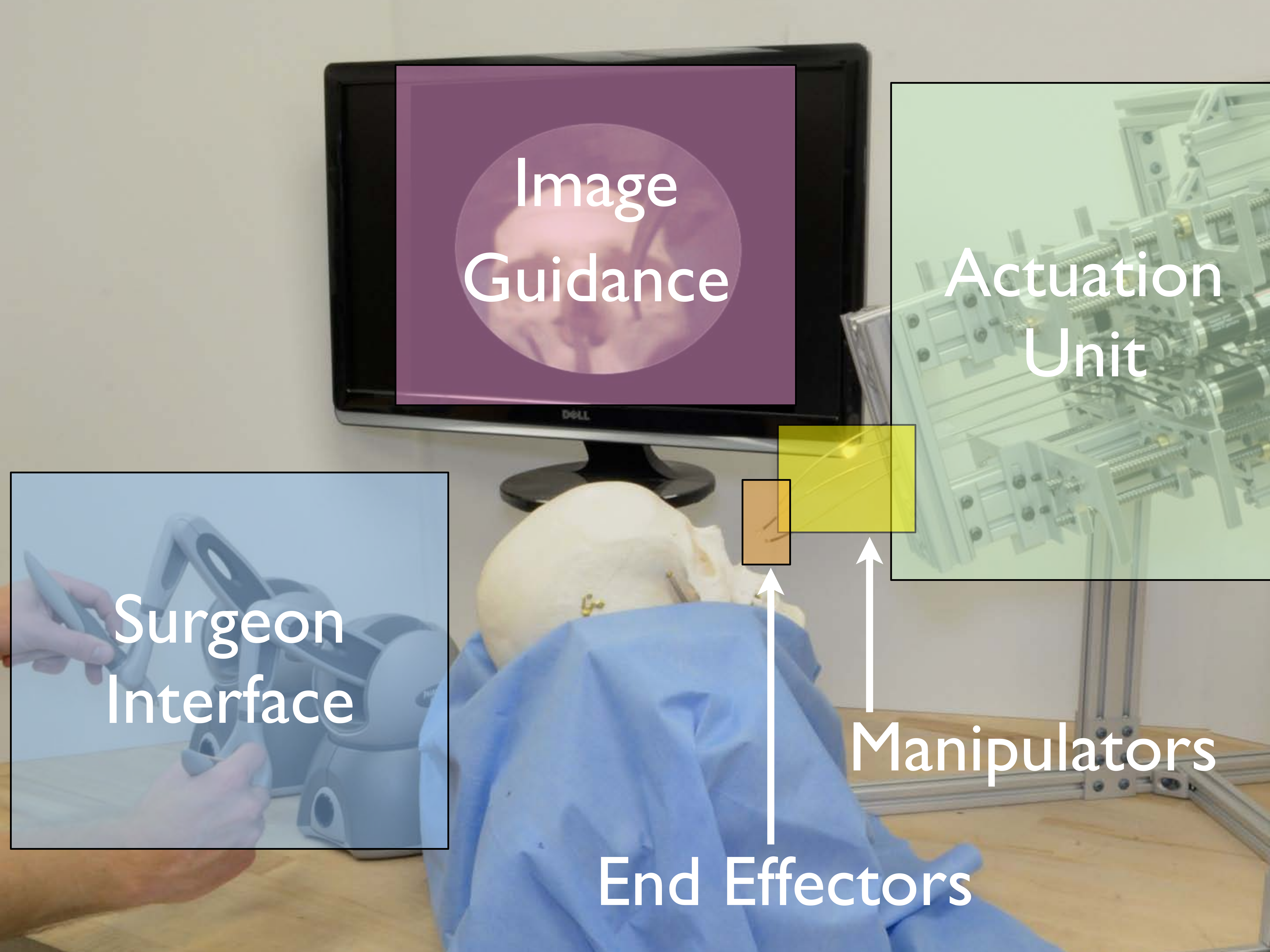
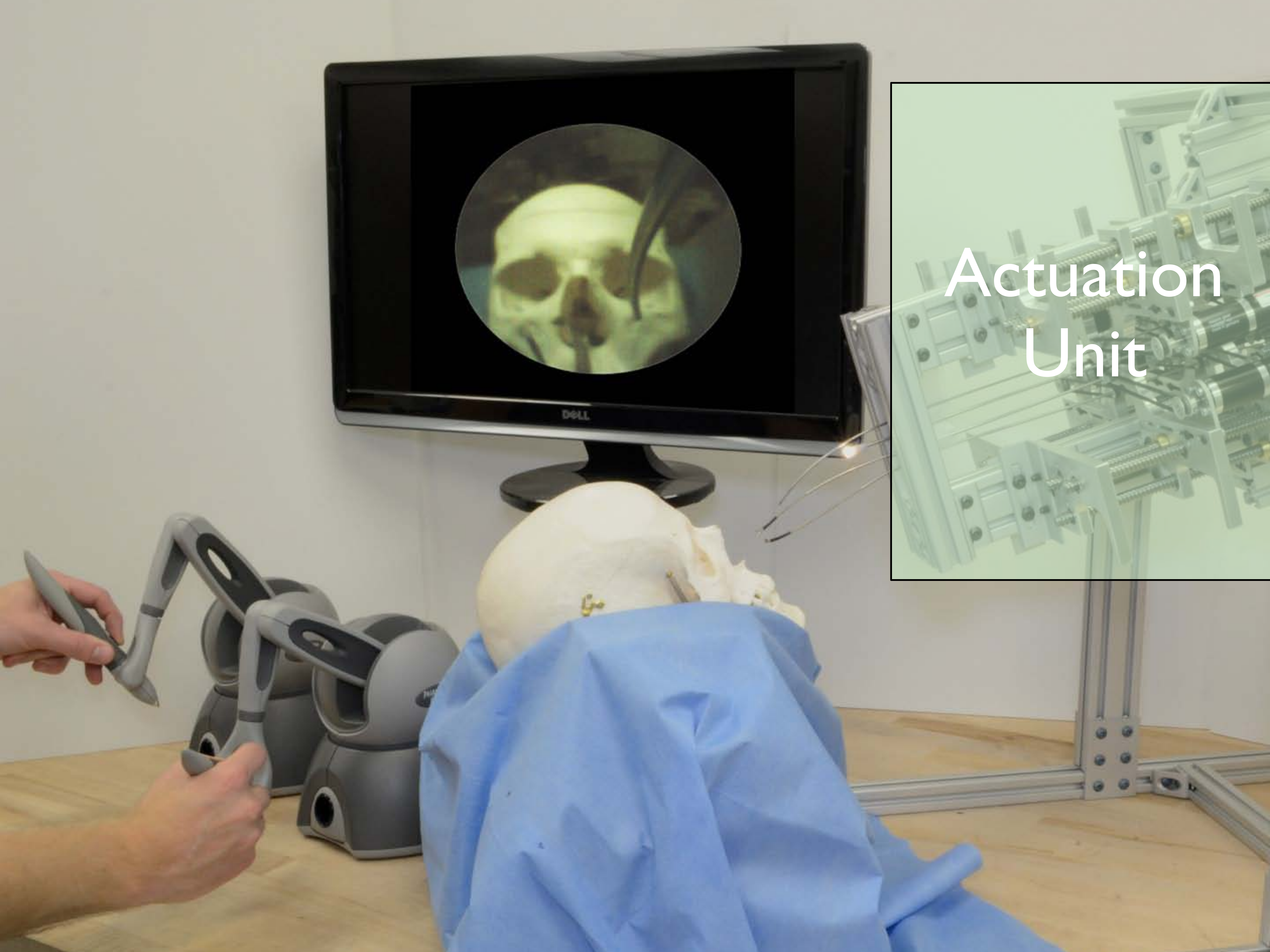
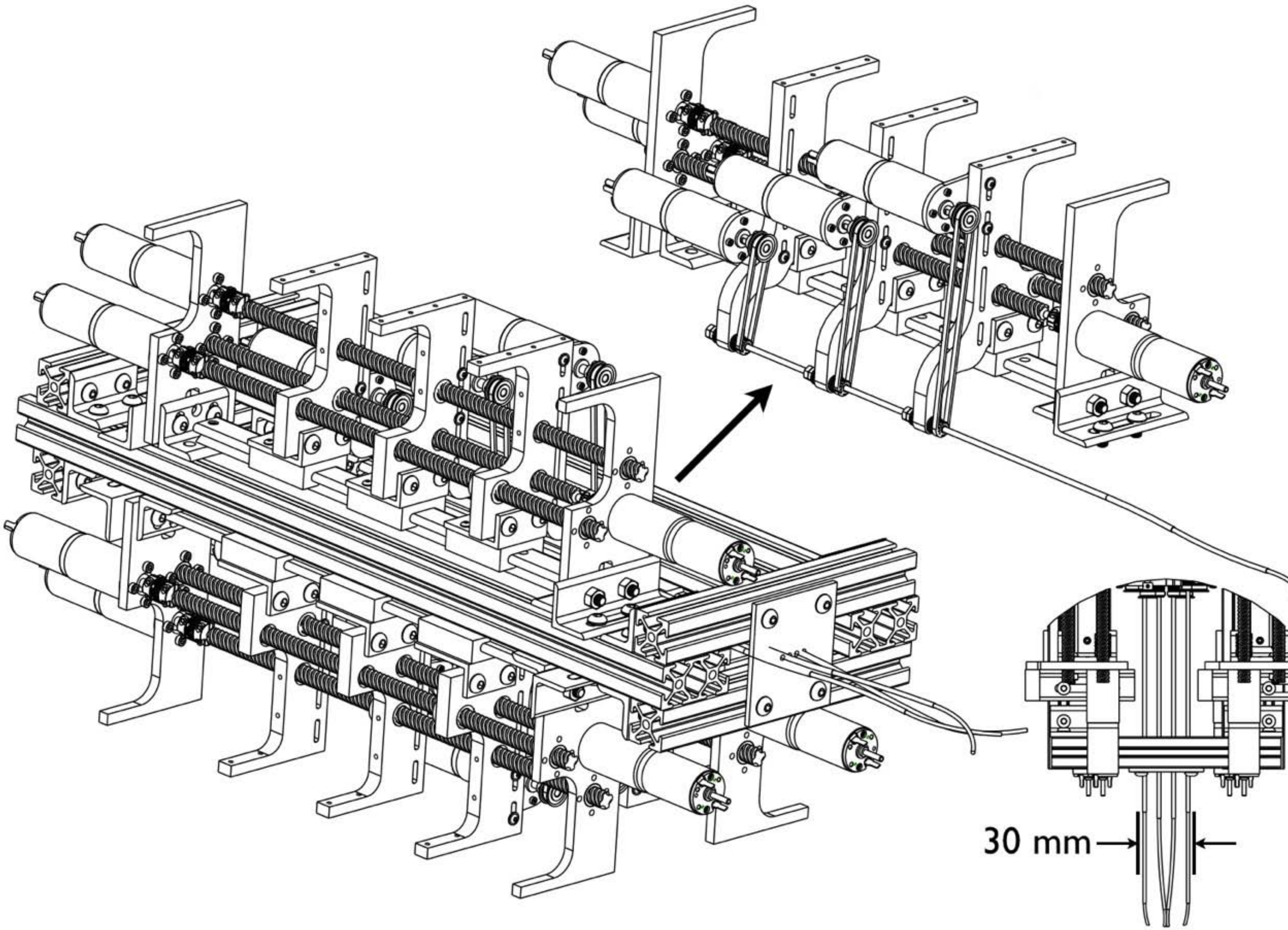


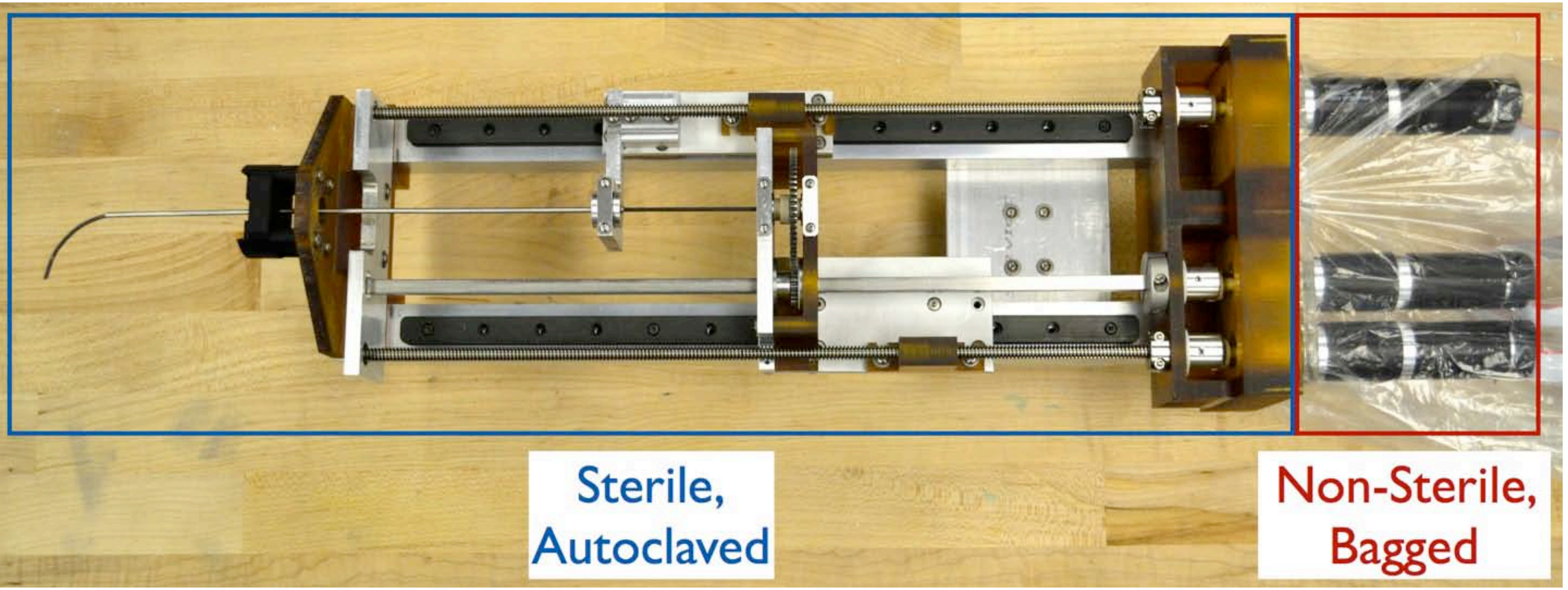
Image Guidance
Actuation Unit
Surgeon Interface
Manipulators
End Effectors

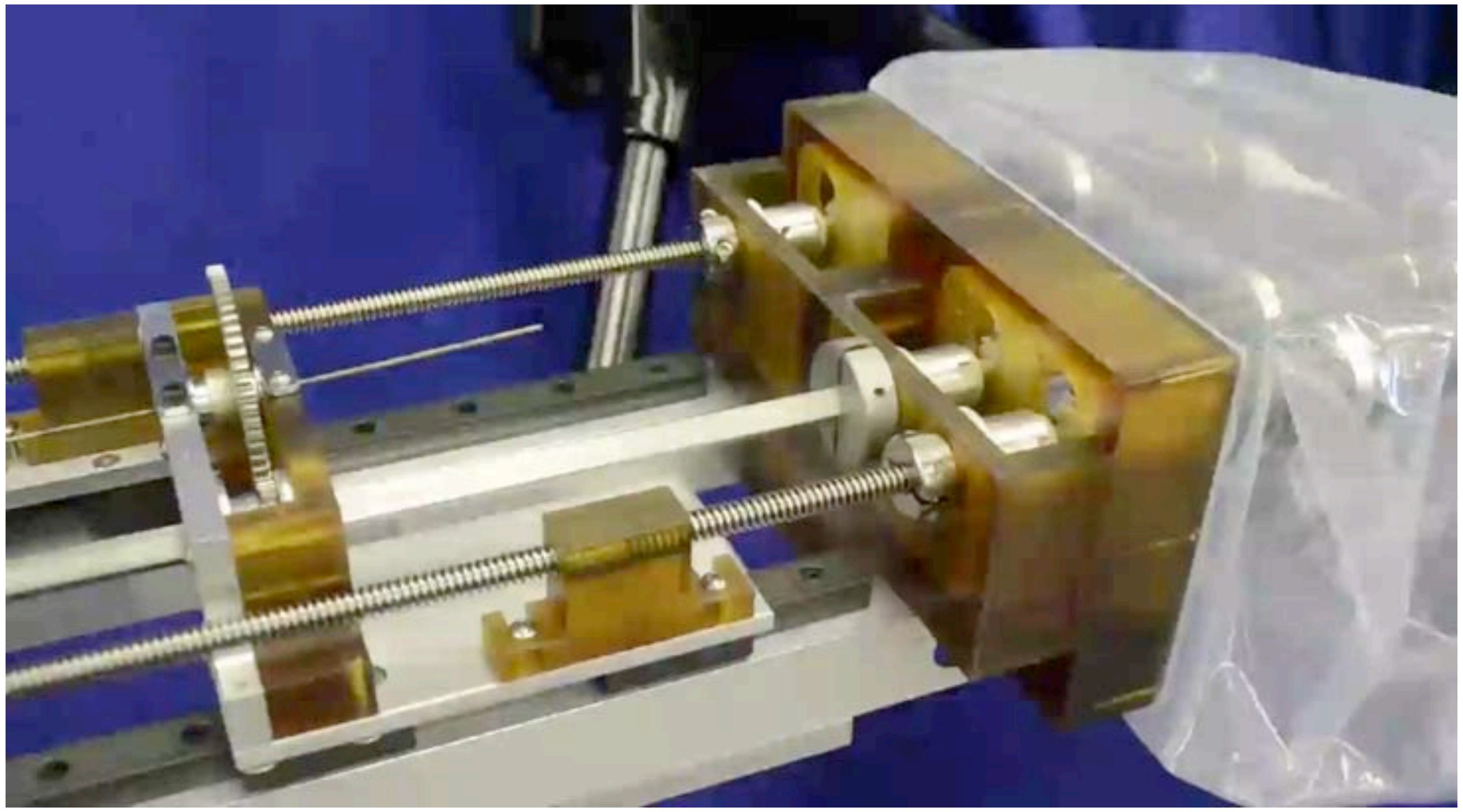

Actuation
Unit
DELL

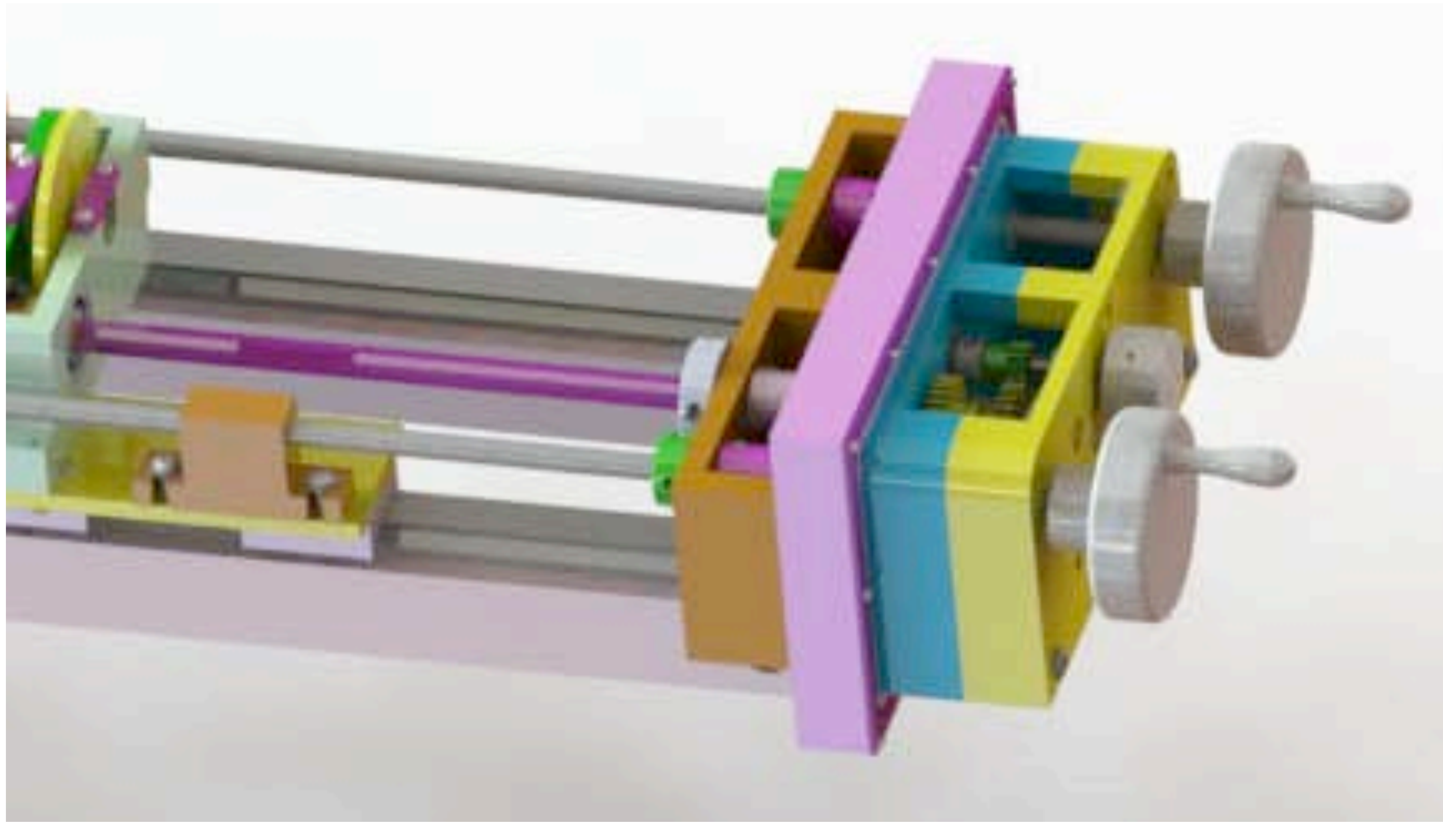
Quadramanual Design Concept



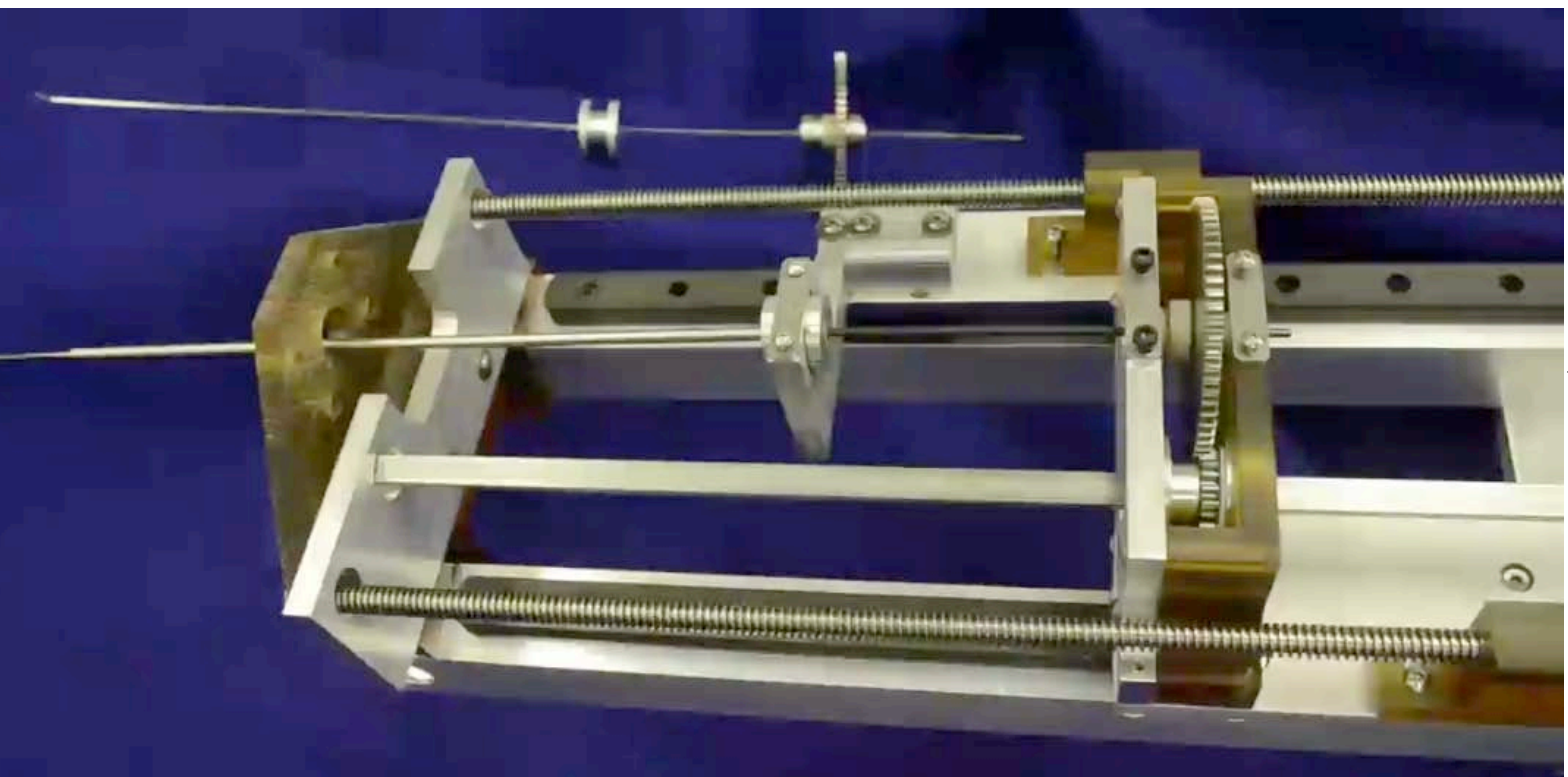
Biocompatible, Sterilizable Robot Design







Bagging
Procedure



Tube Change
Procedure

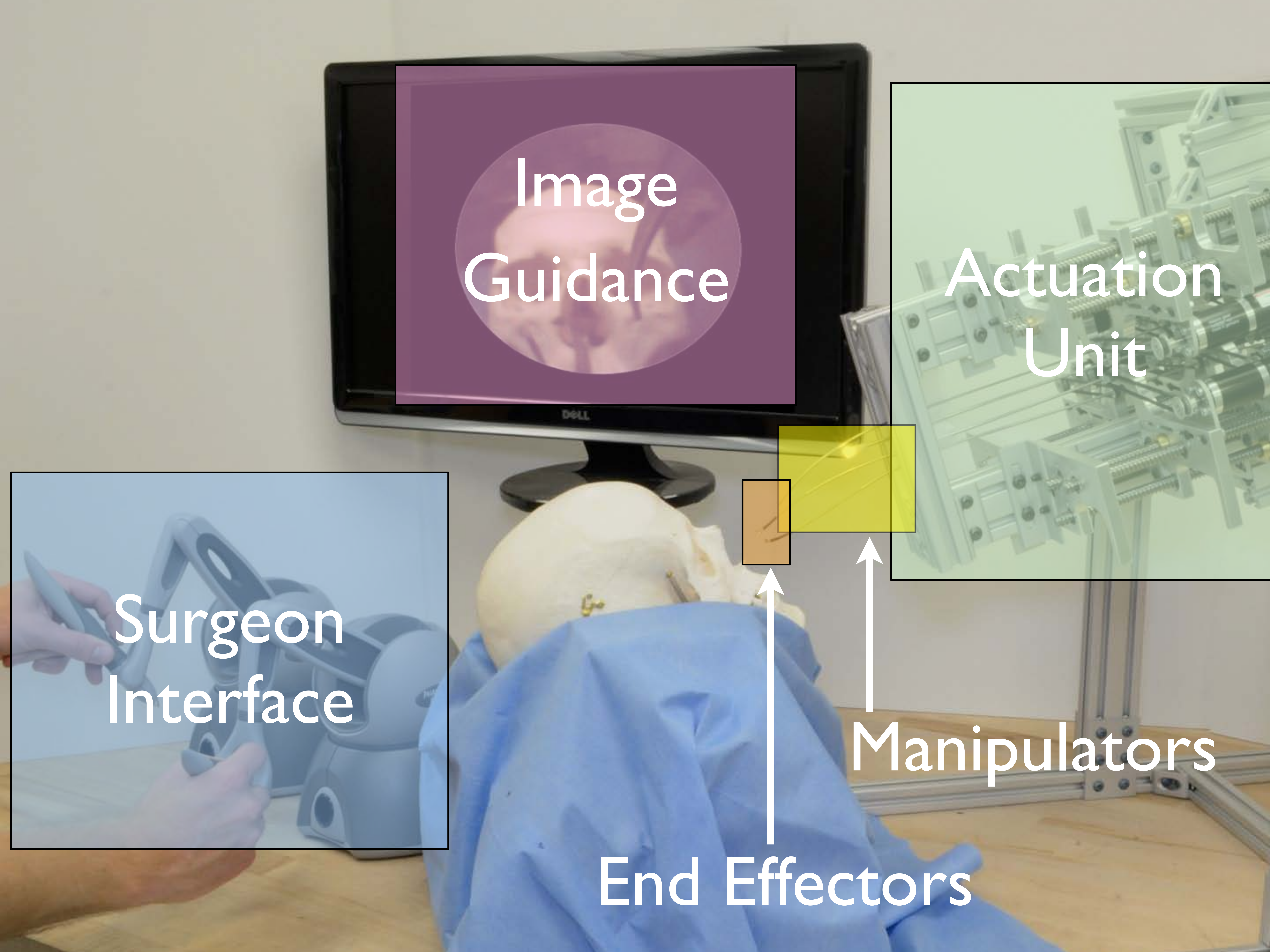
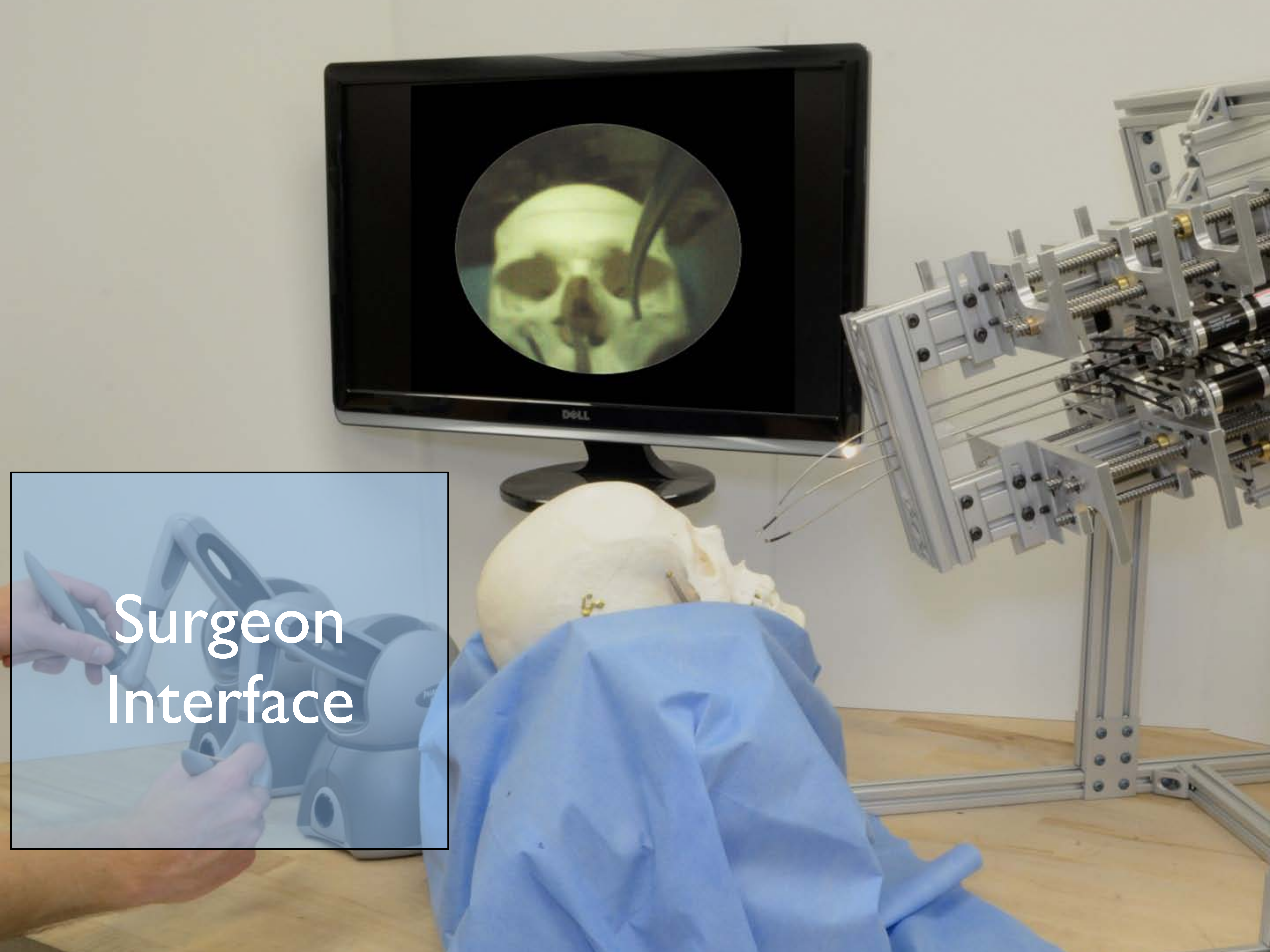
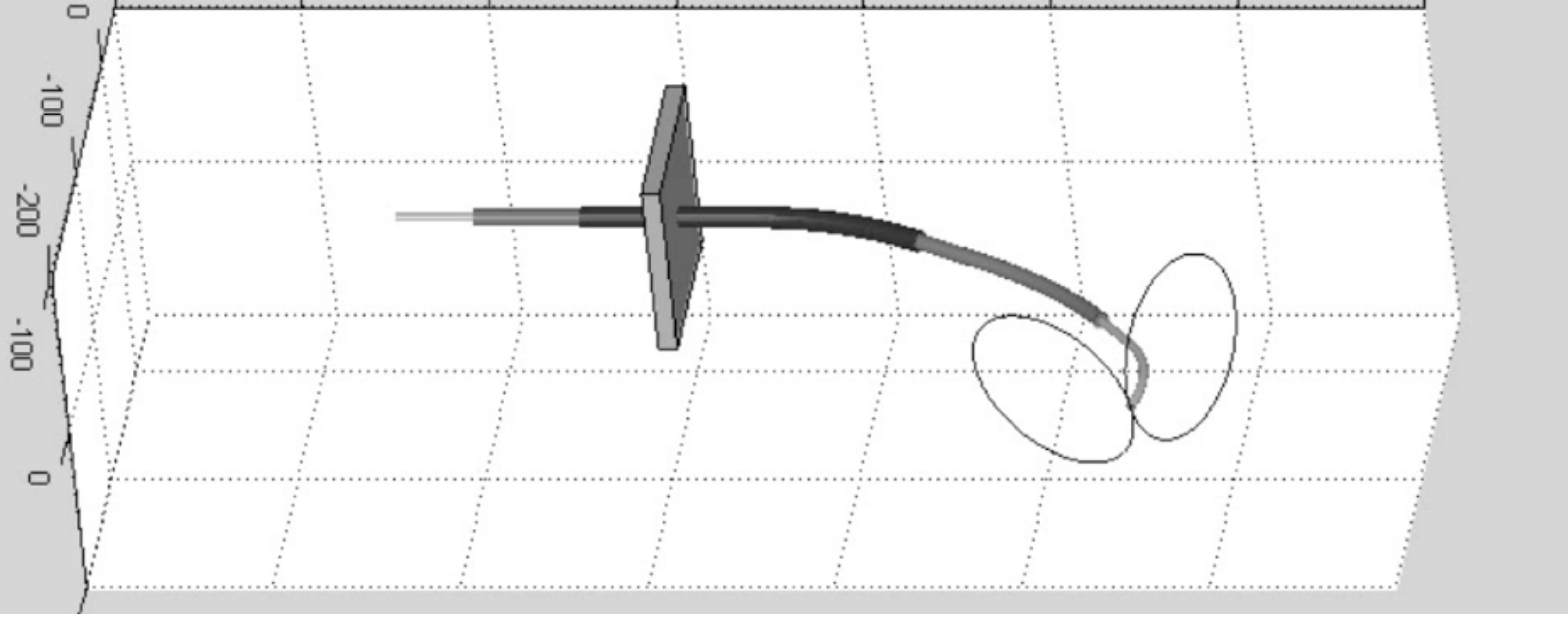
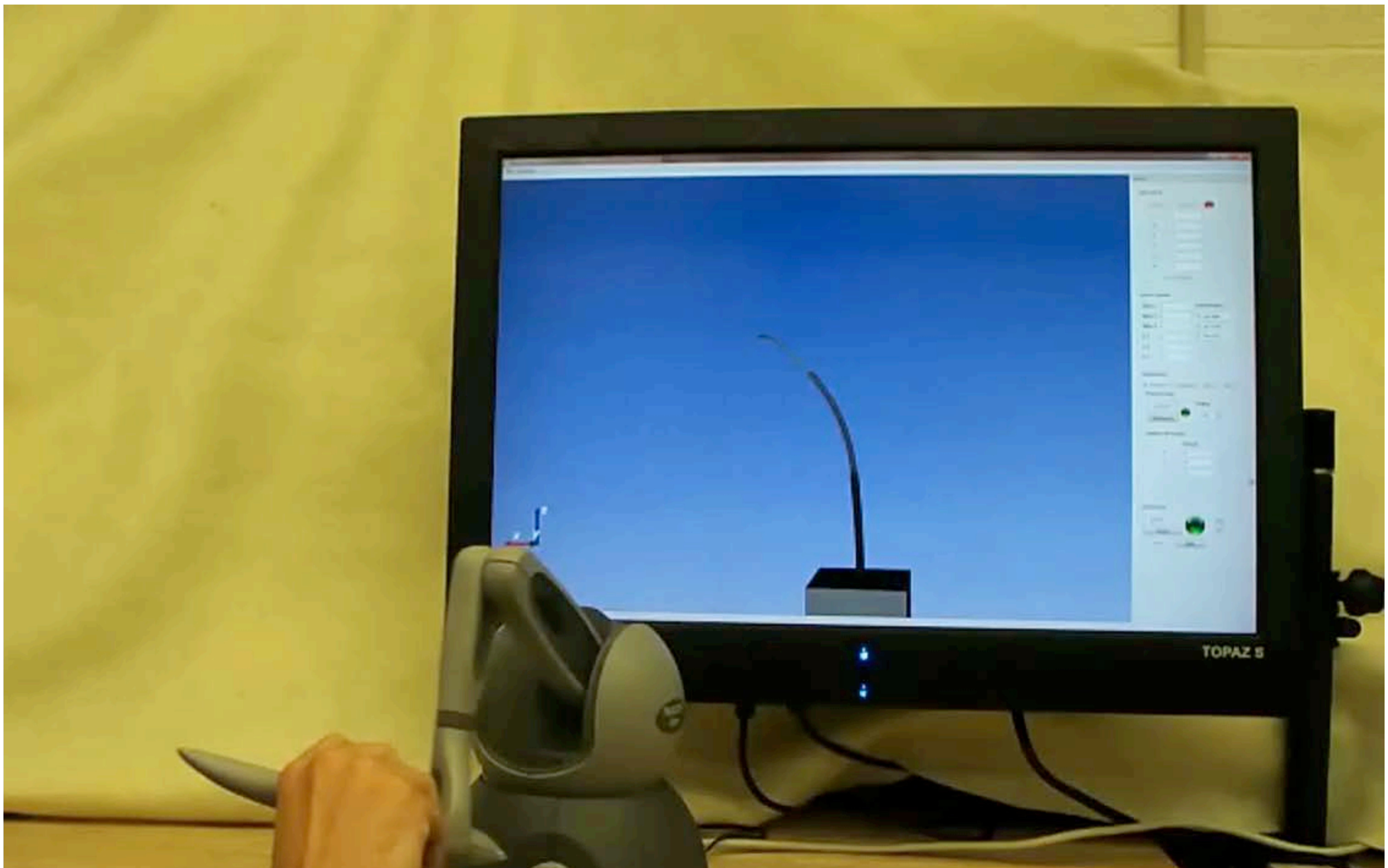


Image Guidance
Actuation Unit
Surgeon Interface
Manipulators
End Effectors

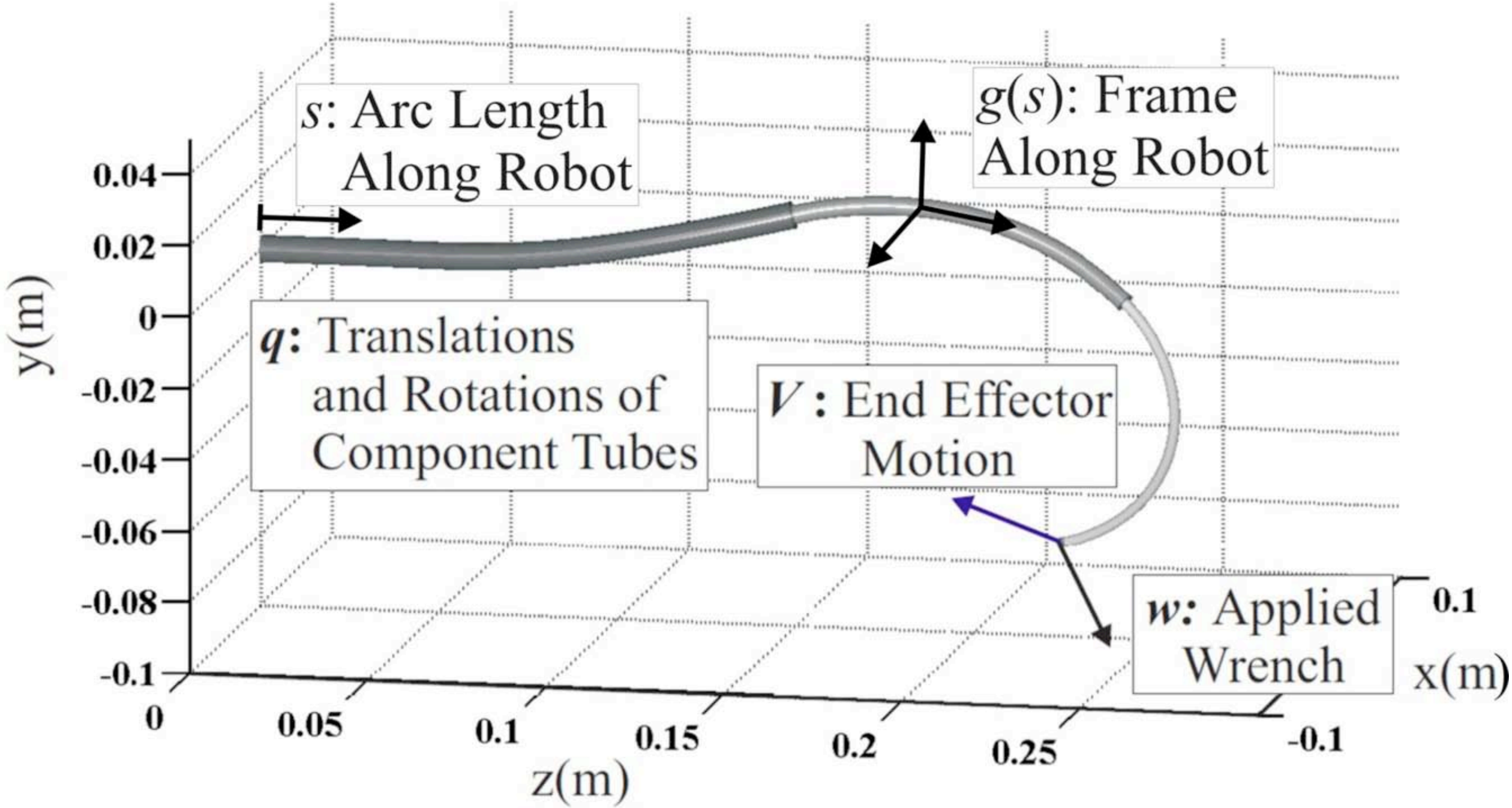

DELL
Surgeon
Interface

Trajectory Following and Teleoperation





Mechanics-Based Model for Concentric-Tube Robots



INPUTS:
Actuators, ***q***
Loads, ***w***

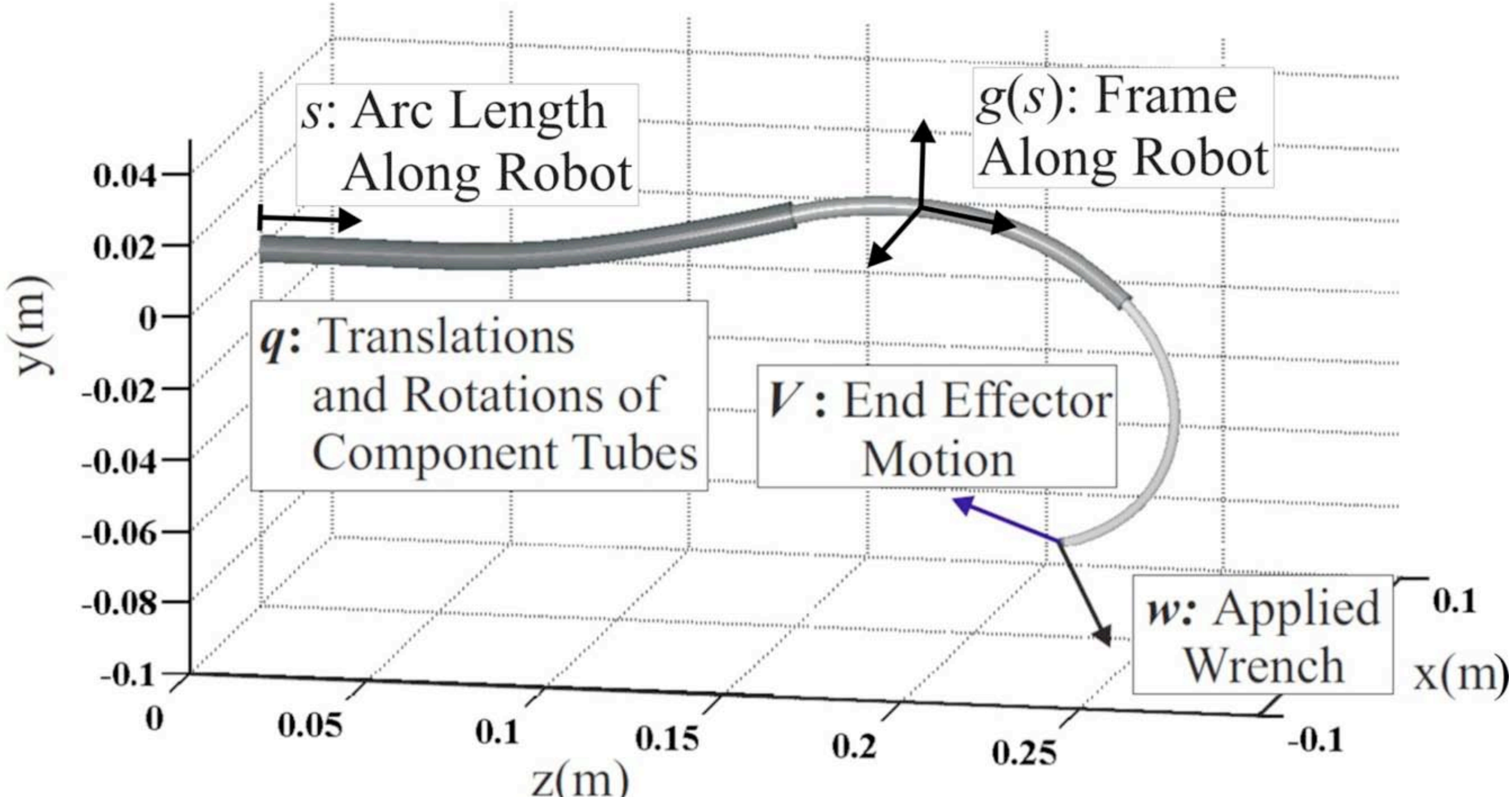
→

Model:
Nonlinear BVP

→

OUTPUTS:
Robot Shape, ***g***(s)

Mechanics-Based Model for Concentric-Tube Robots

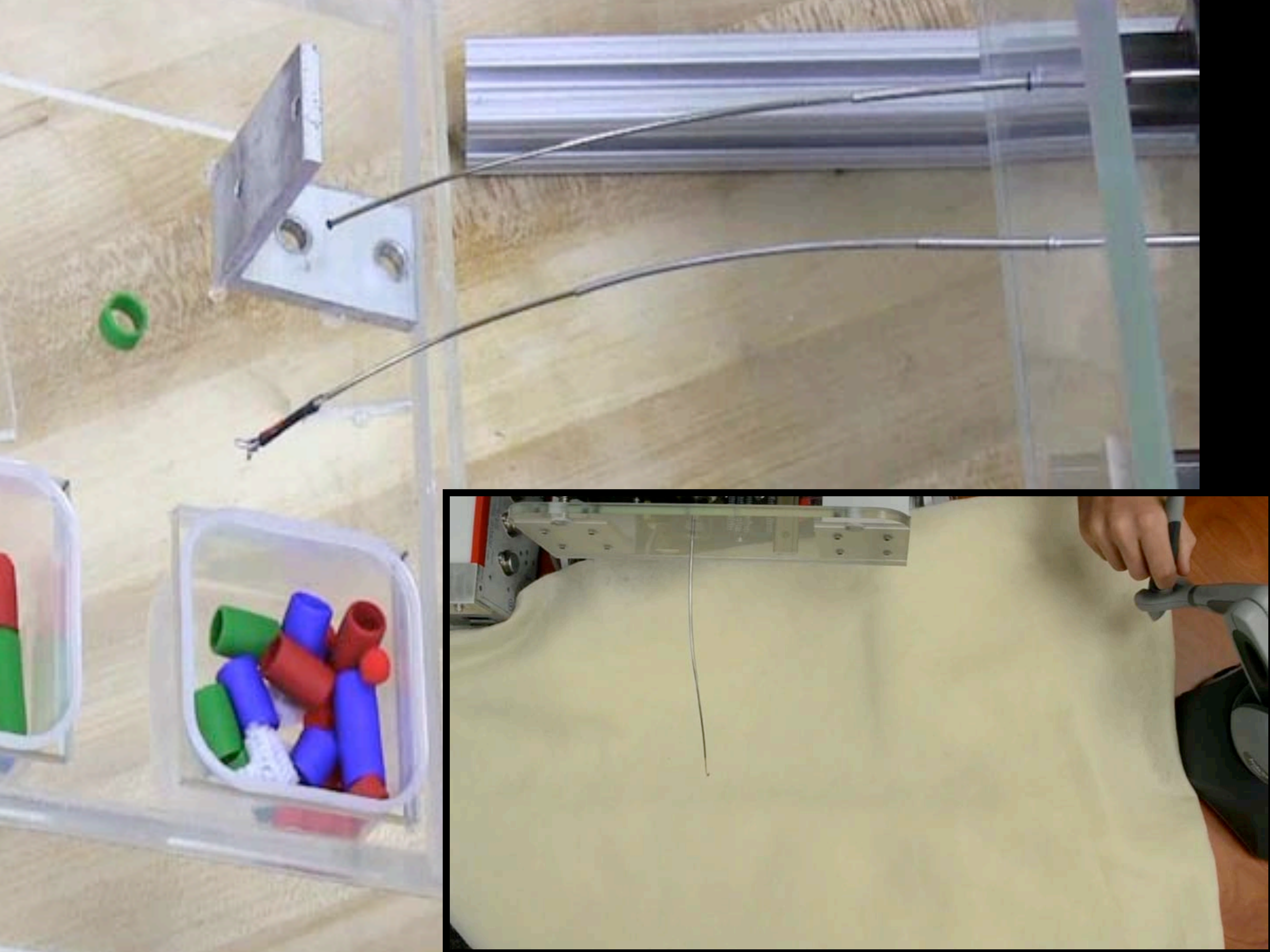


$$\mathbf{V} = J(s, \mathbf{q}, \mathbf{w})\dot{\mathbf{q}} + C(s, \mathbf{q}, \mathbf{w})\dot{\mathbf{w}}$$

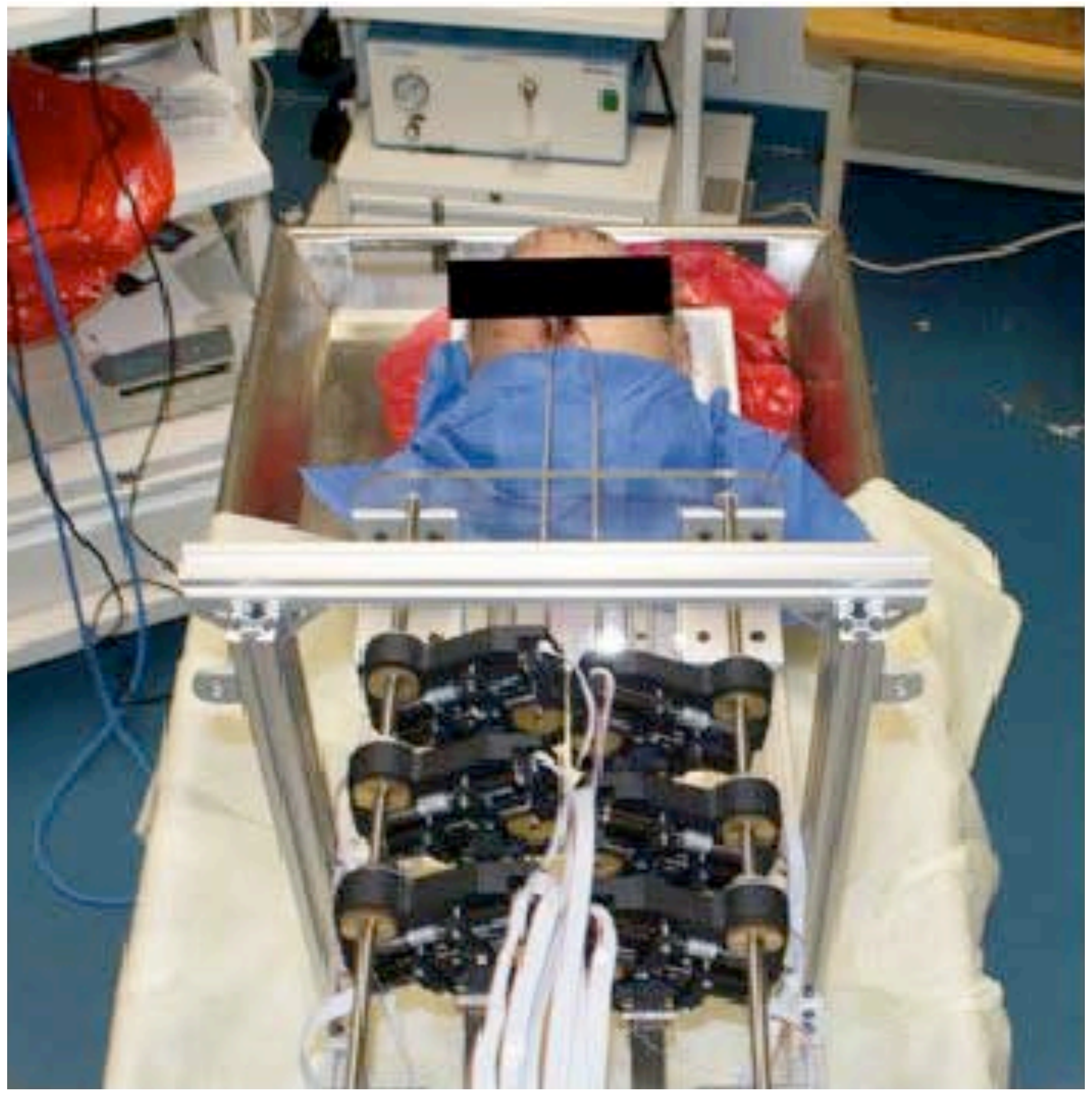
Jacobian — Compliance Matrix

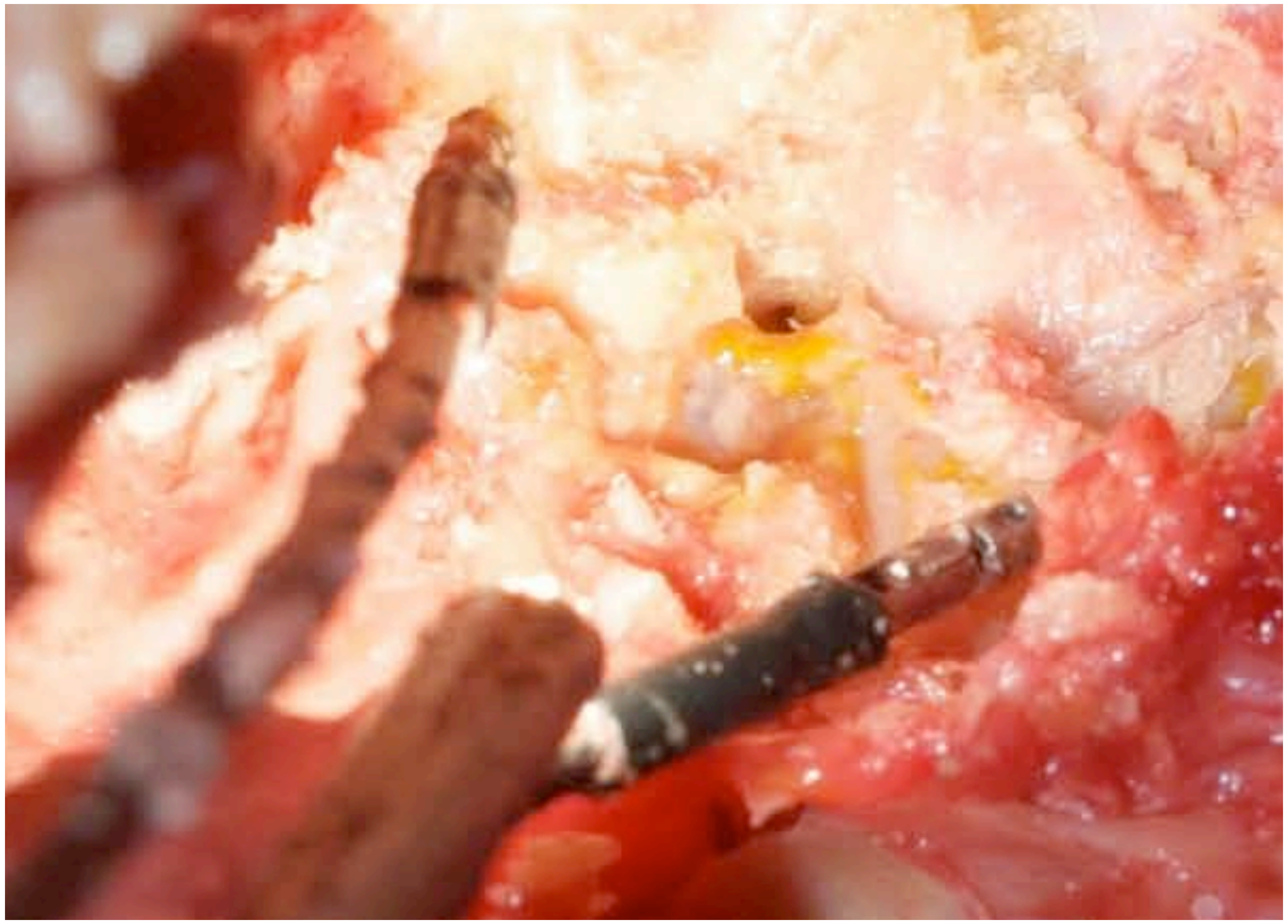
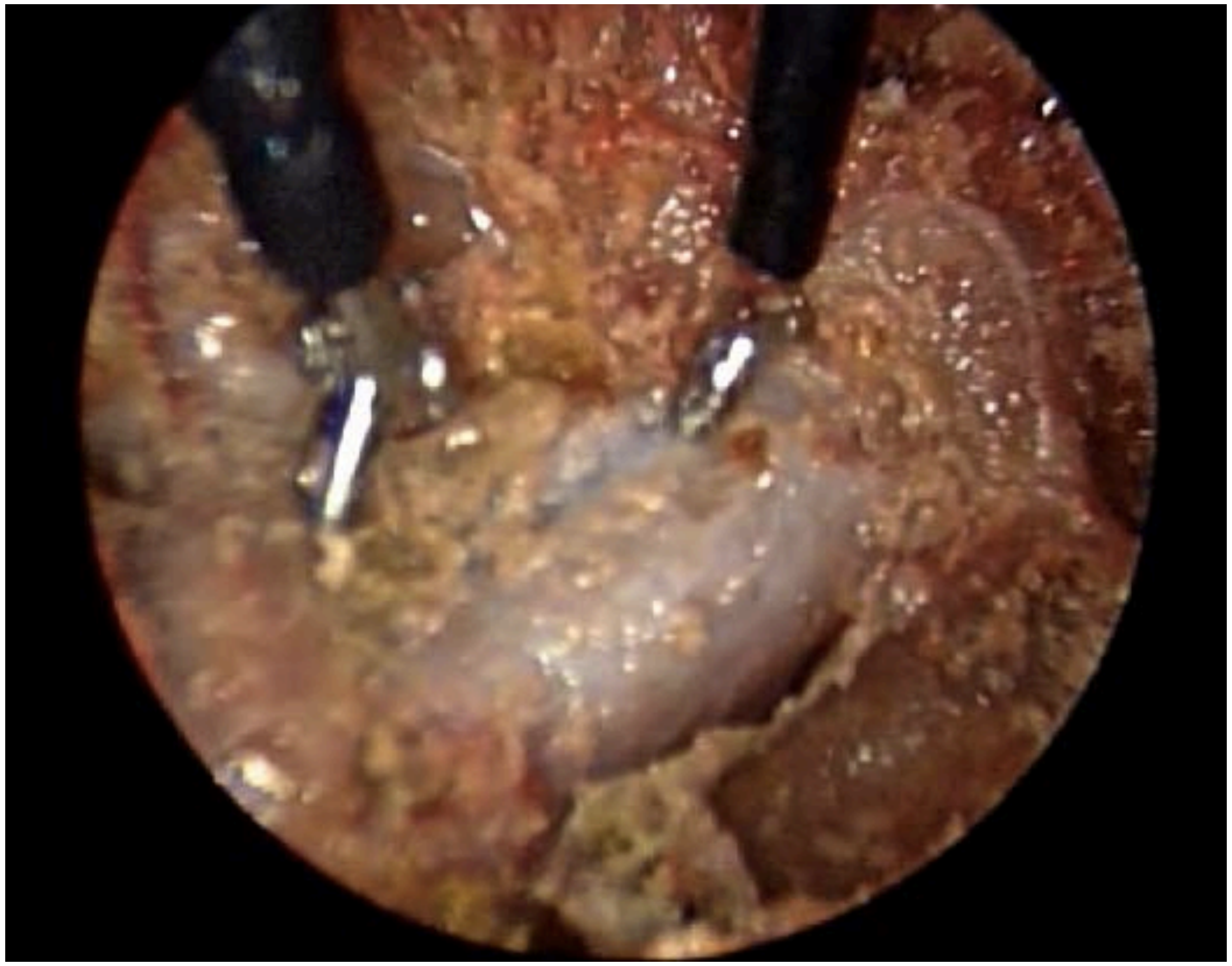
Can compute these (unloaded) at 1kHz in C++ ! Loaded approx. 300 Hz

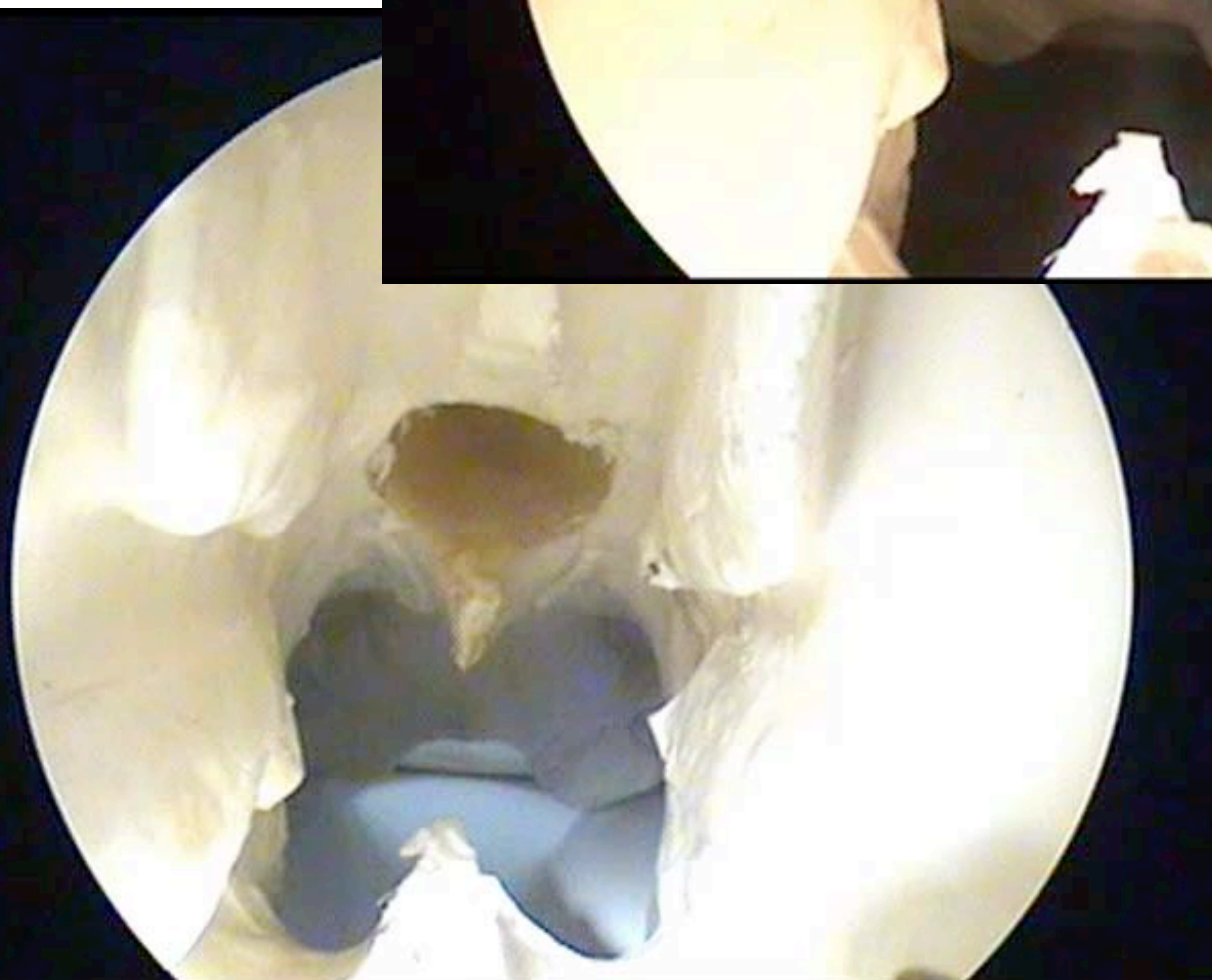
Rucker and Webster, "Computing Jacobians and Compliance Matrices for Externally Loaded Continuum Robots. ICRA 2011.



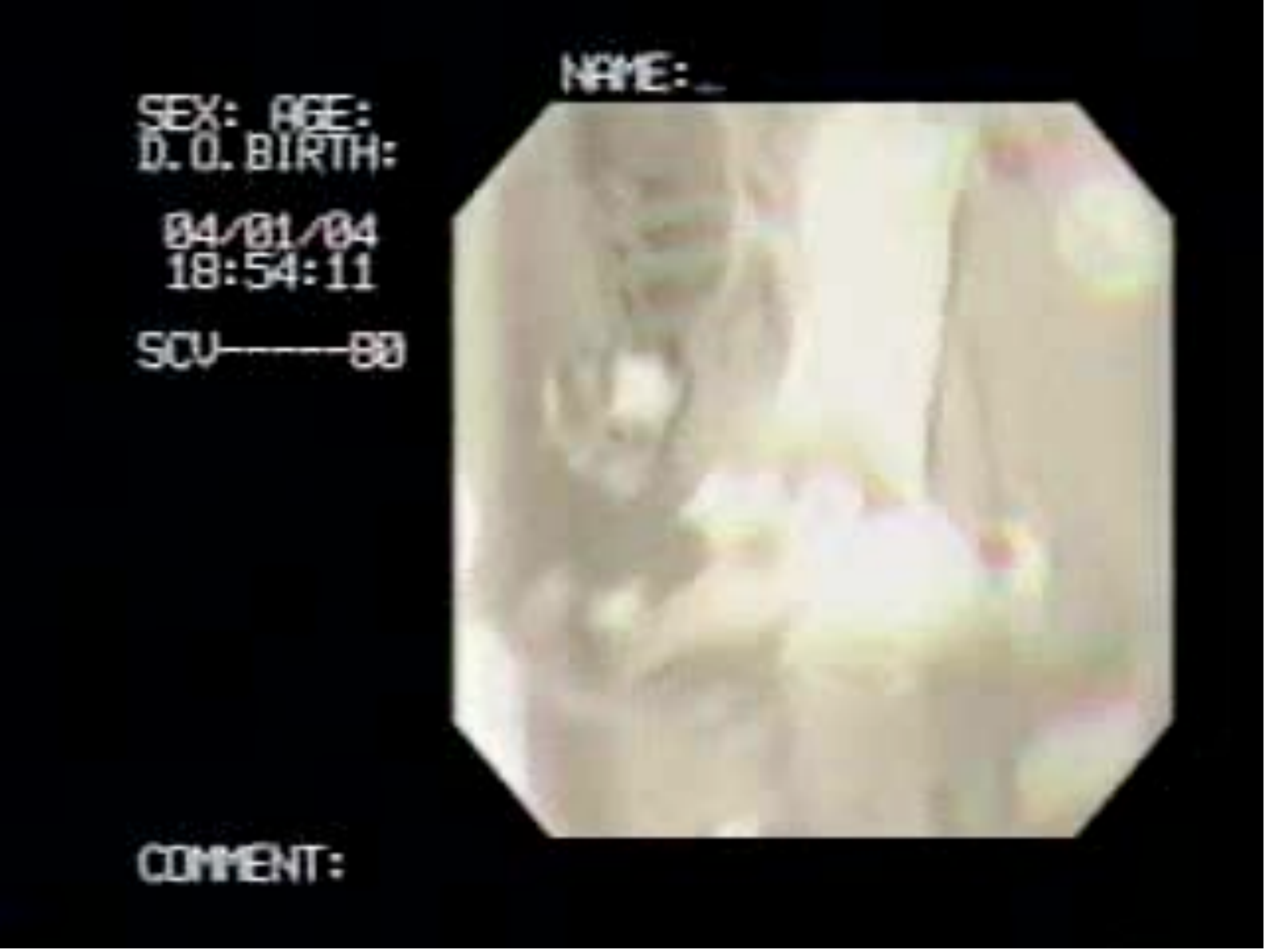
Experiments

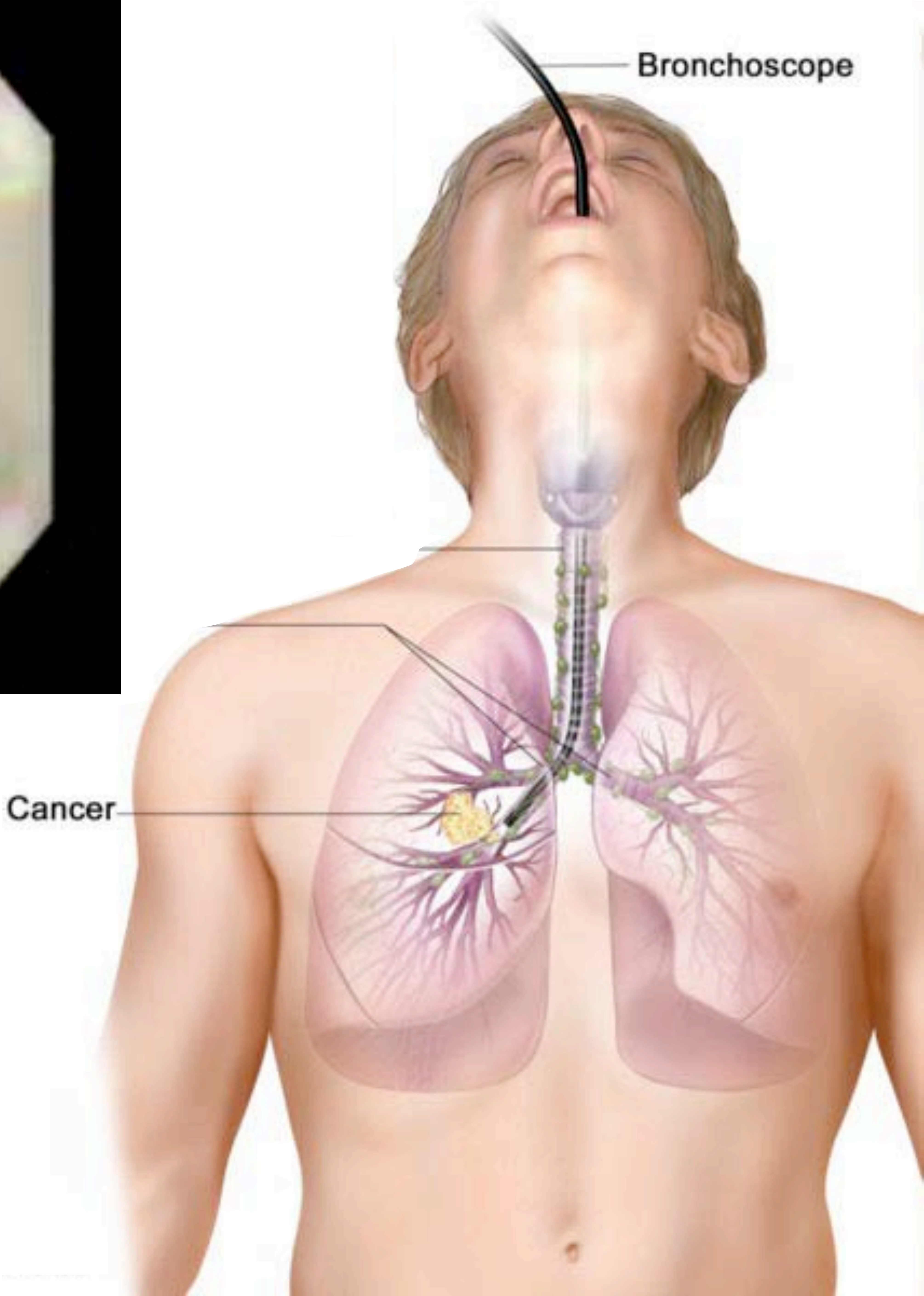



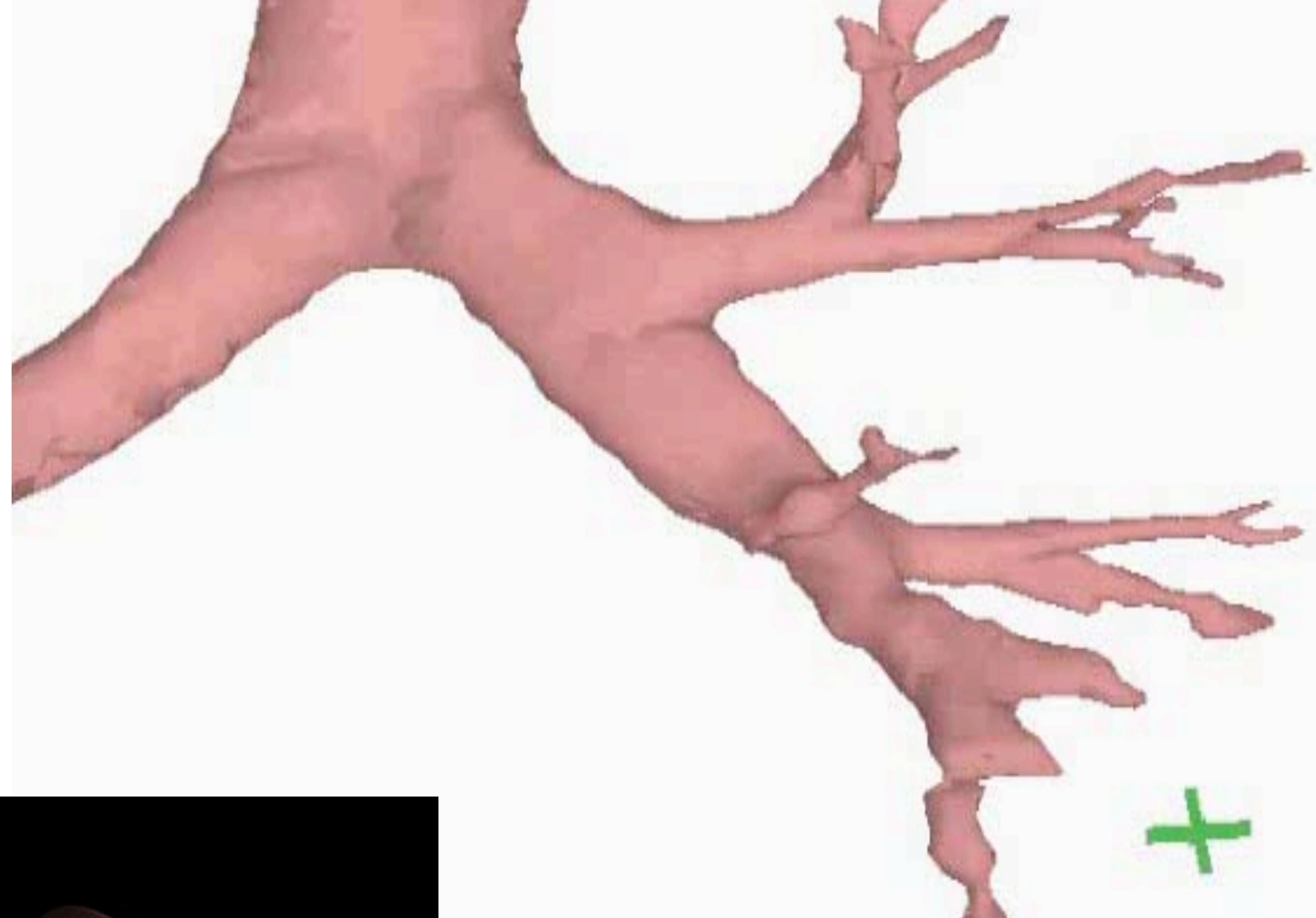


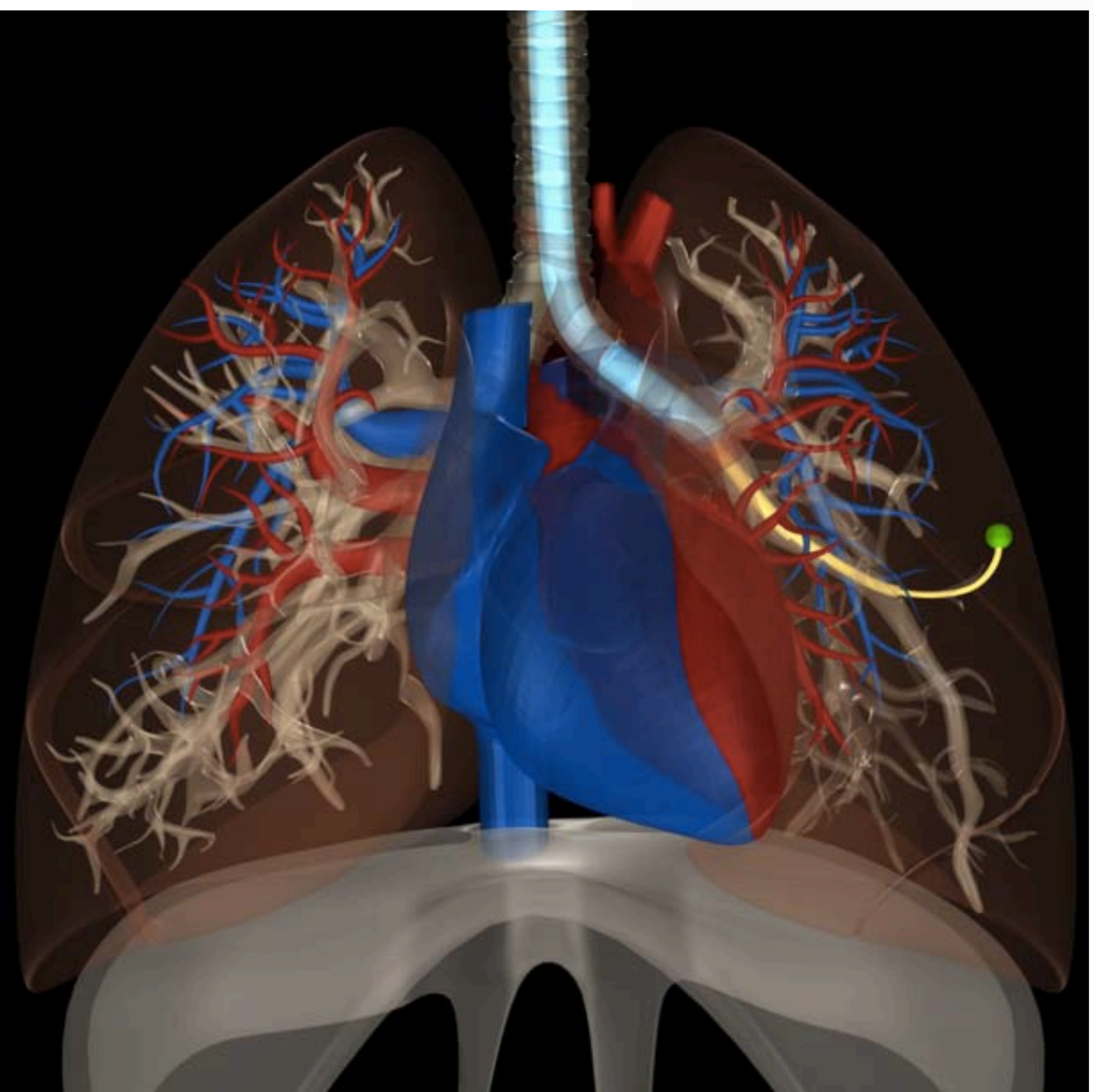
What Else Might It Do?

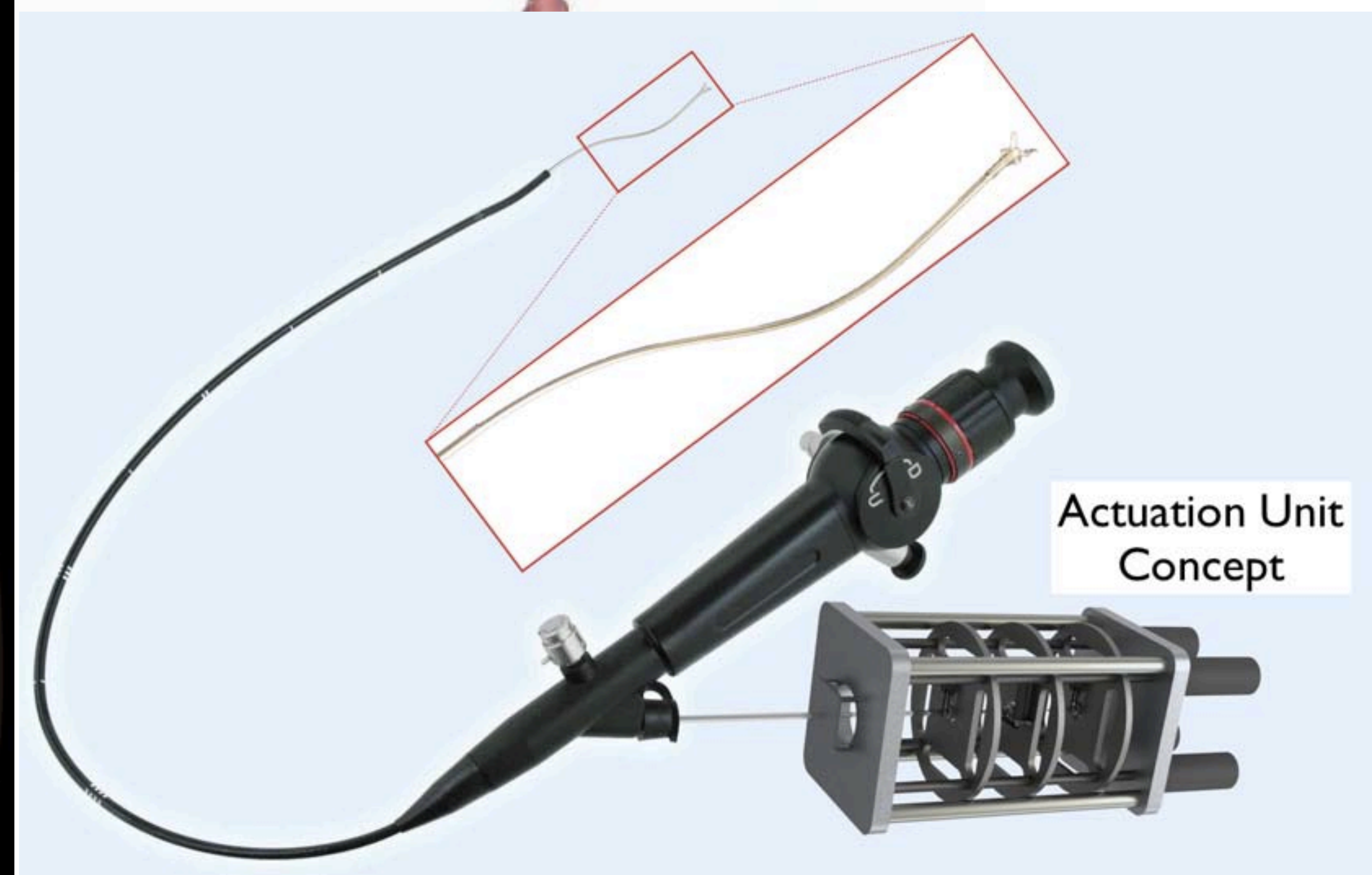

NAME:_
SEX: AGE:
D.O.BIRTH:
04/01/04
18:54:11
SCV------80
COMMENT:


Bronchoscope
Cancer

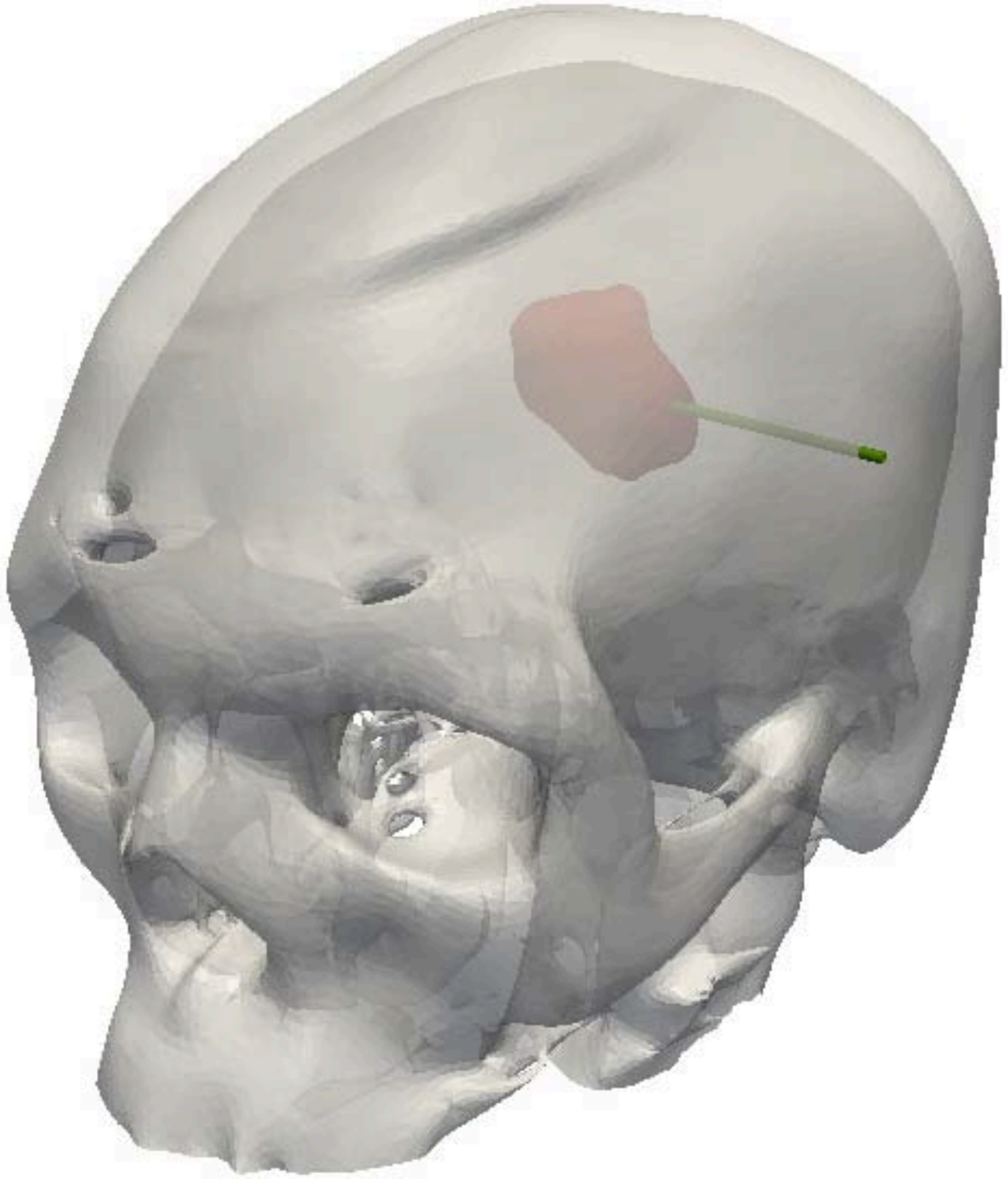
Lung System Concept, Planning & Simulation

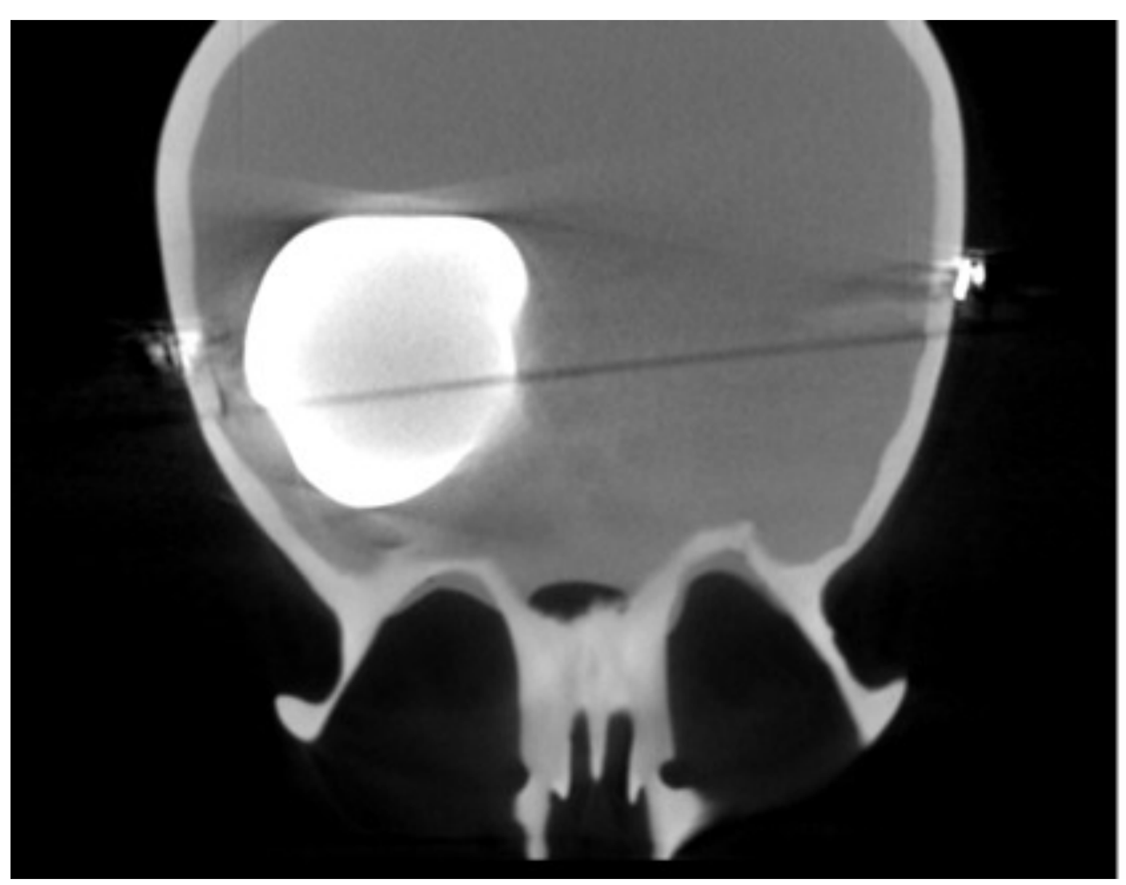


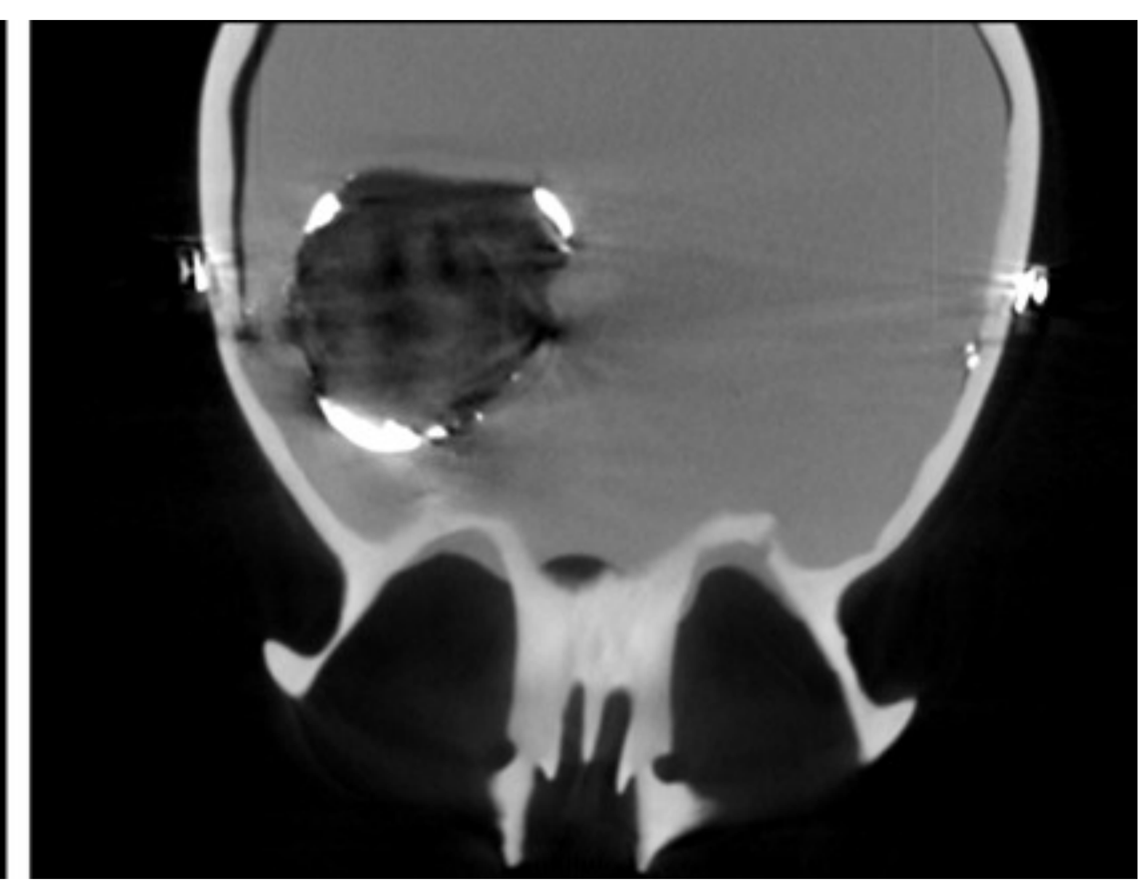




Intracerebral Percutaneous Intervention

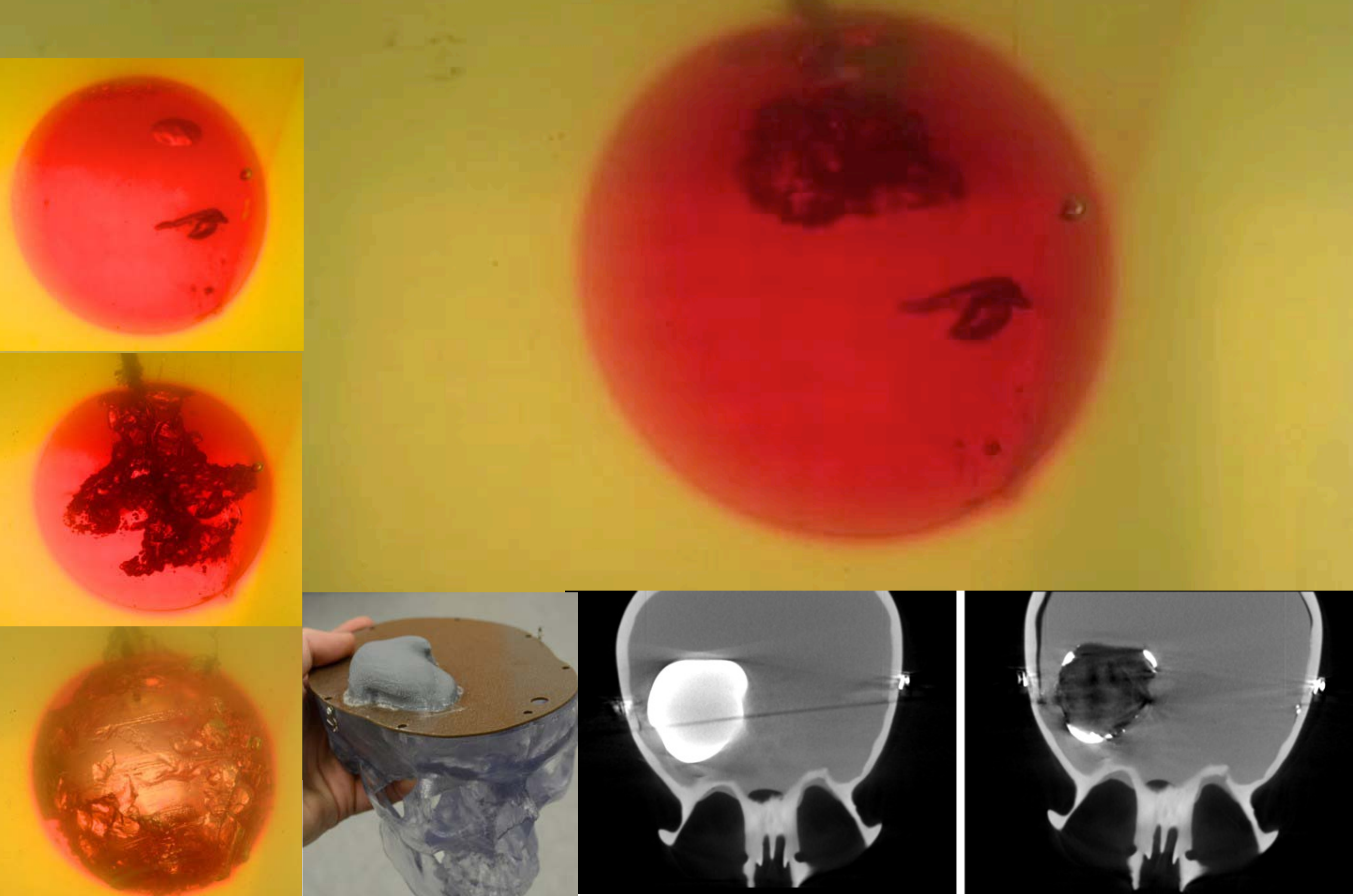




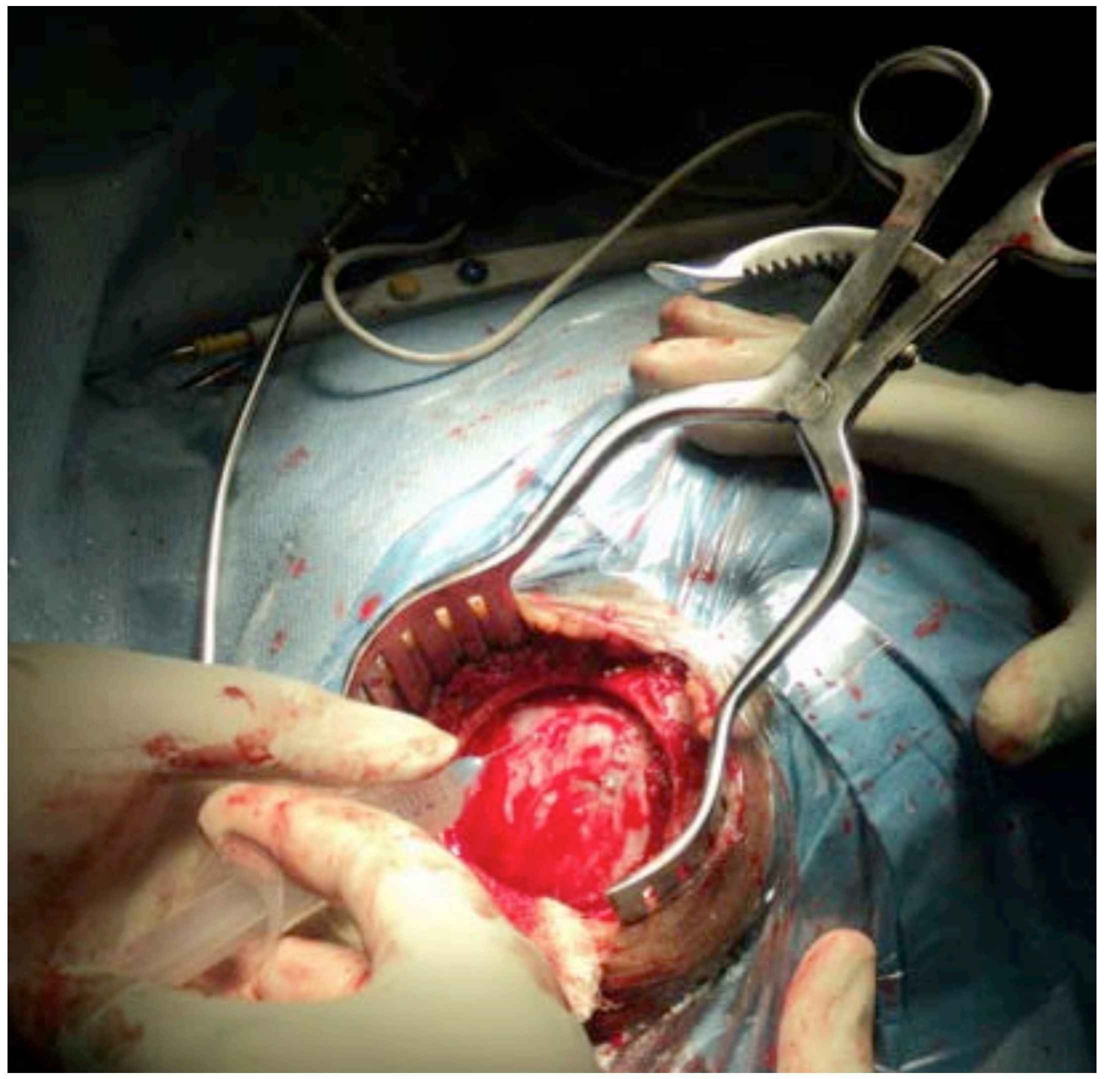


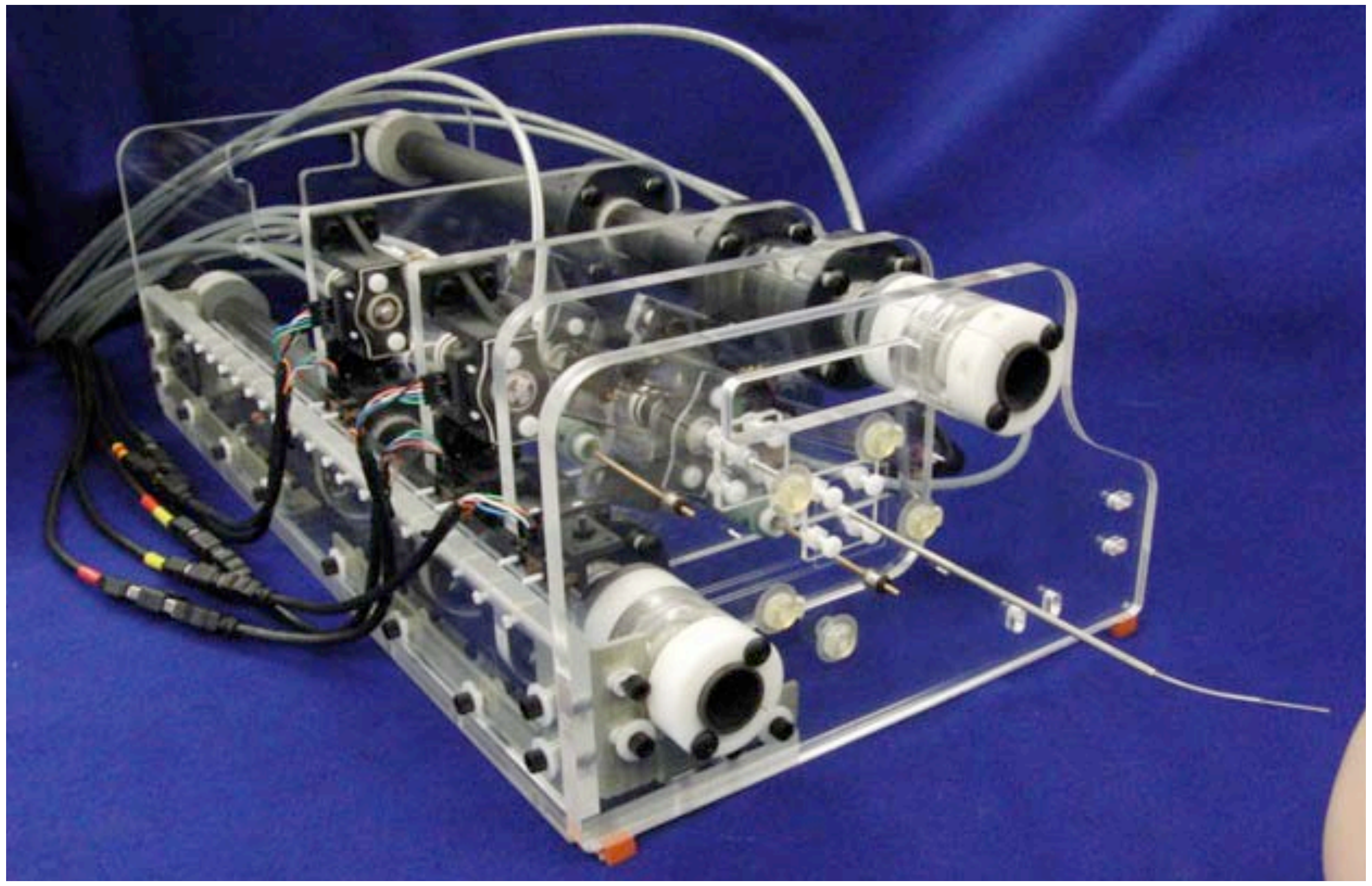
Burgner, Swaney, Lathrop, Weaver, and Webster, "Debulking From Within: A Robotic Steerable Cannula for Intracerebral Hemorrhage Evacuation," TBME (In Press).

In Vitro Experiment

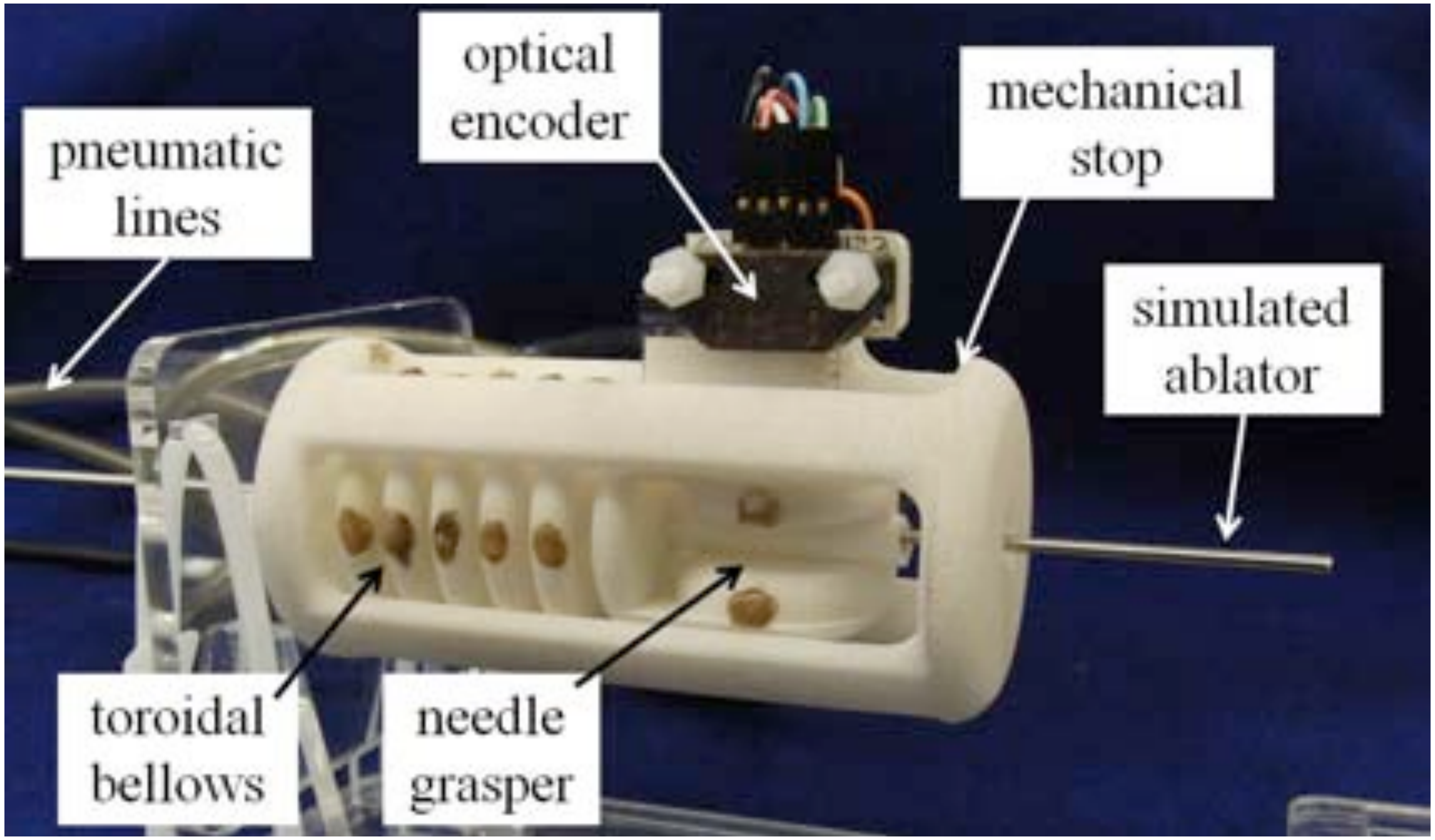


MRI Compatible Robot For Epilepsy





Comber, Barth, and Webster, "MR-Compatible Precision Pneumatic Active Cannula Robot," ASME J. Med. Devices (In Press).



Comber, Slightam, Barth, Gervasi, and Webster, "Design and Precision Control of an MR-Compatible Flexible Fluidic Actuator," Fluid Power and Motion Control Conference (In Press).

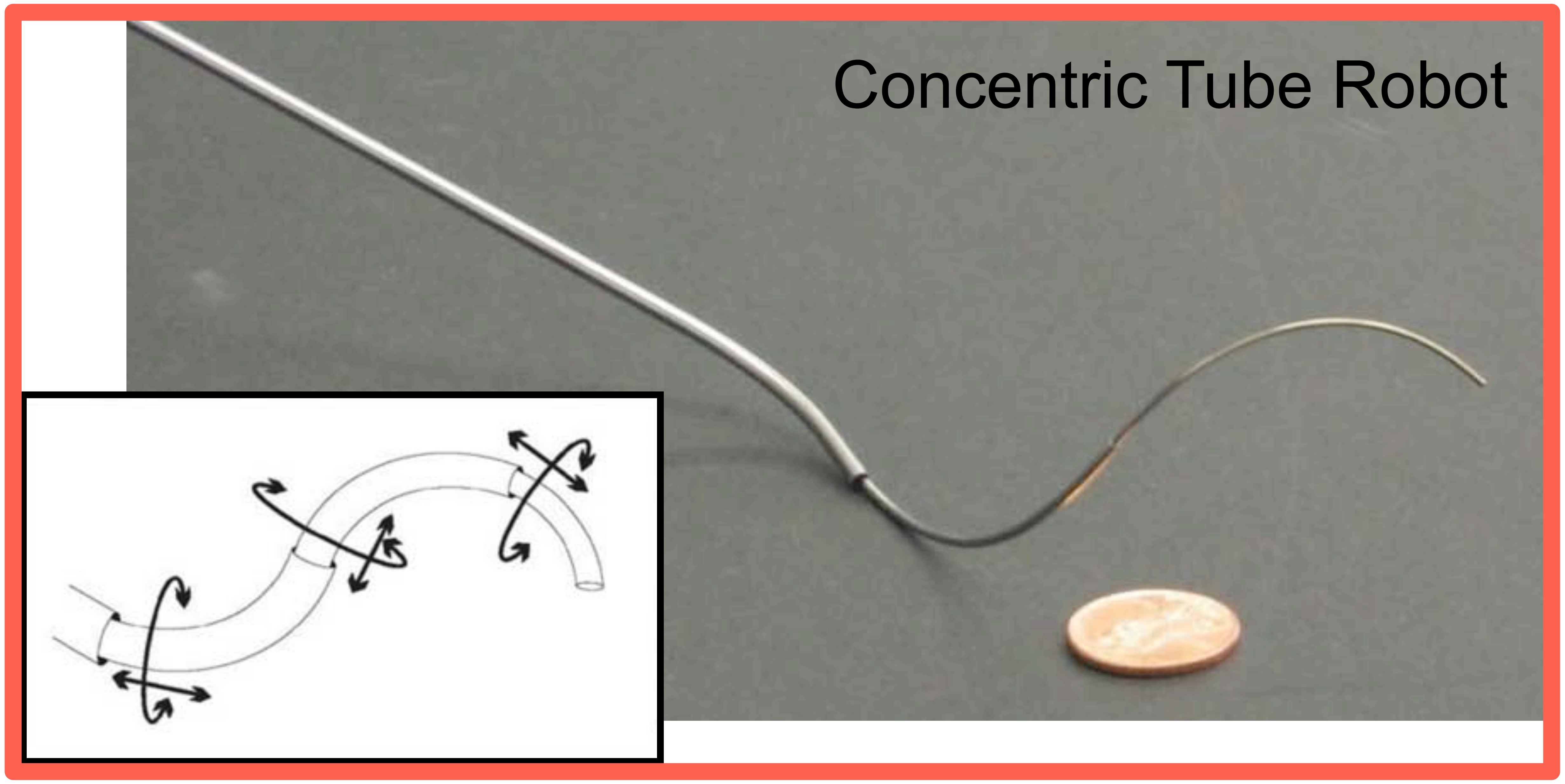

ViewSonic
AURORA

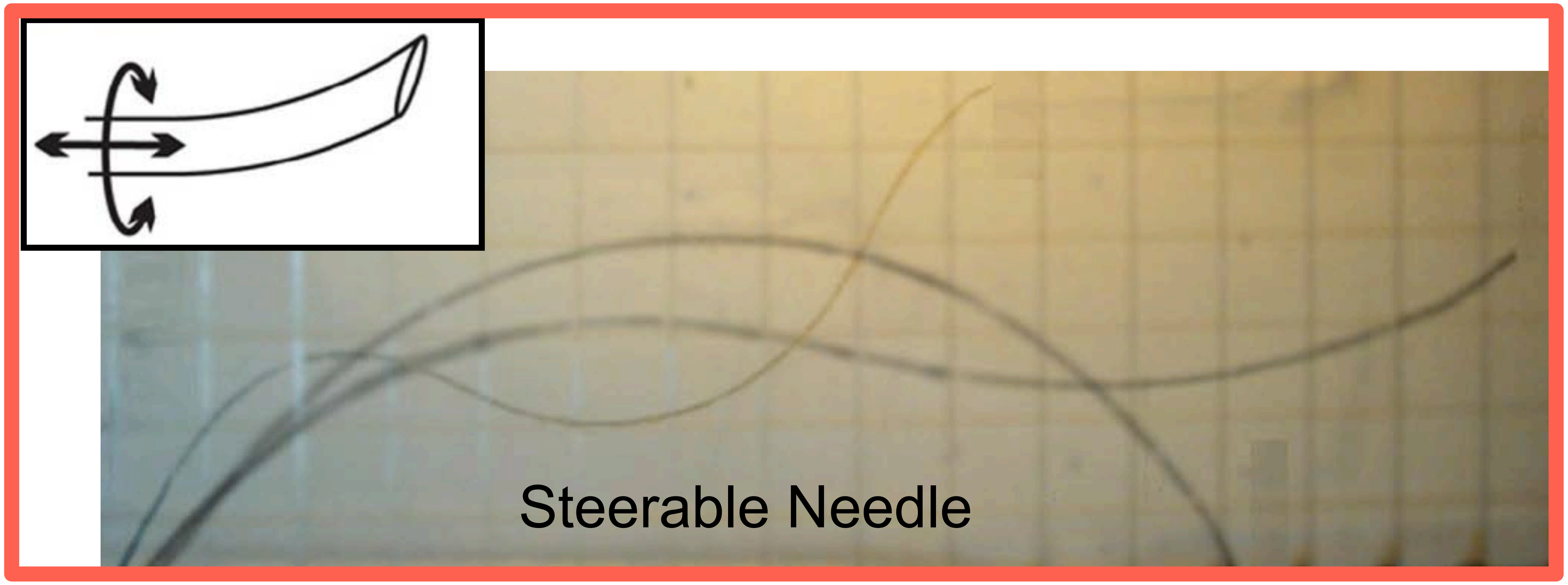

Present
VUMC 2007


Future?


MEDICAL & ELECTROMECHANICAL DESIGN LAB

Examples





Needle Placement Must Be Improved

- High Impact
  - Thousands per day
  - Success depends on accuracy
- Applications
  - Biopsy
  - Thermal ablation
  - Brachytherapy
  - Drug injection
  - And many others…

Tool Positioning and Registration

Image credit: Xu, SPIE '06

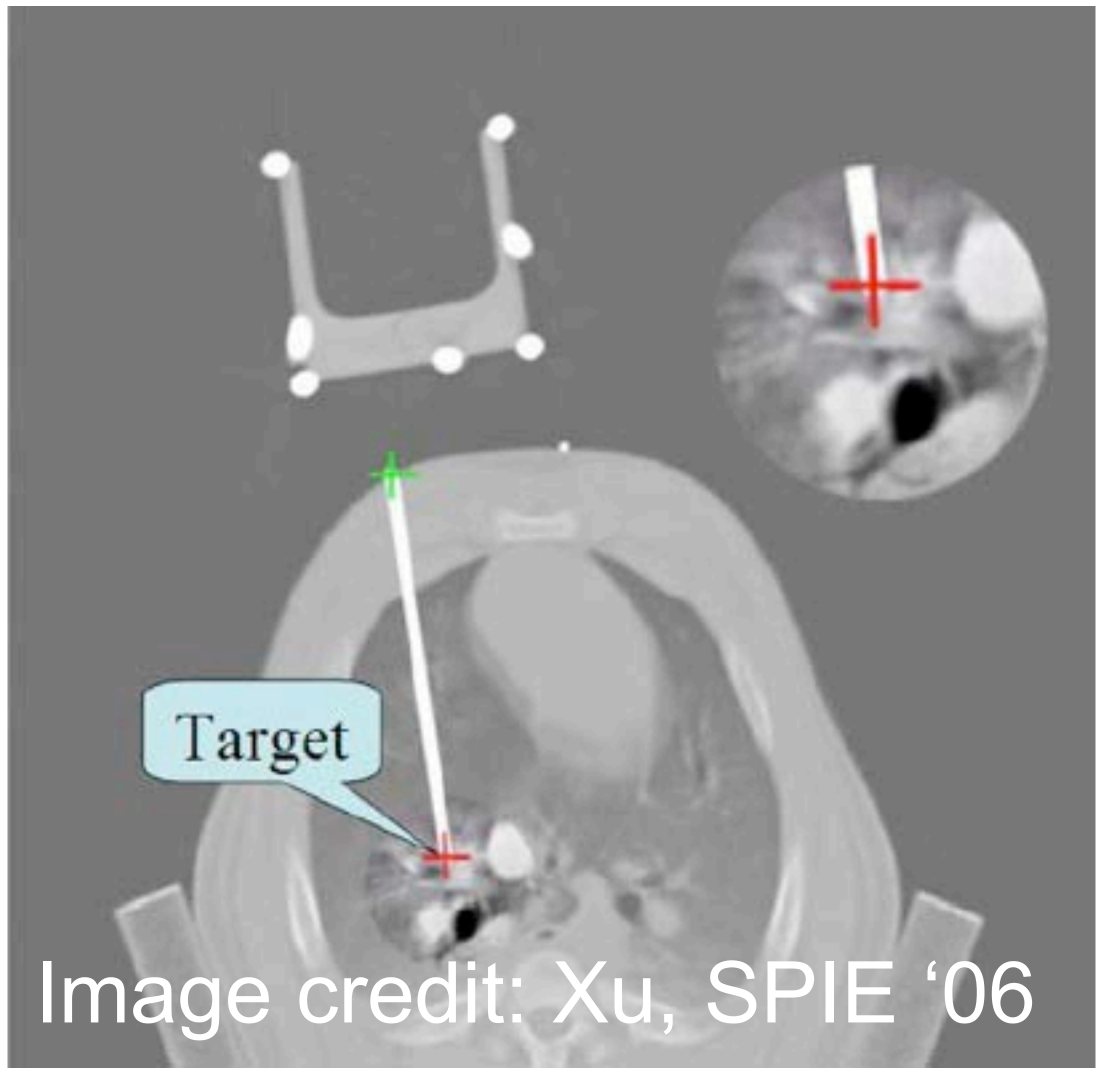


Image credit: Xu, SPIE '06

Why Steer Needles?

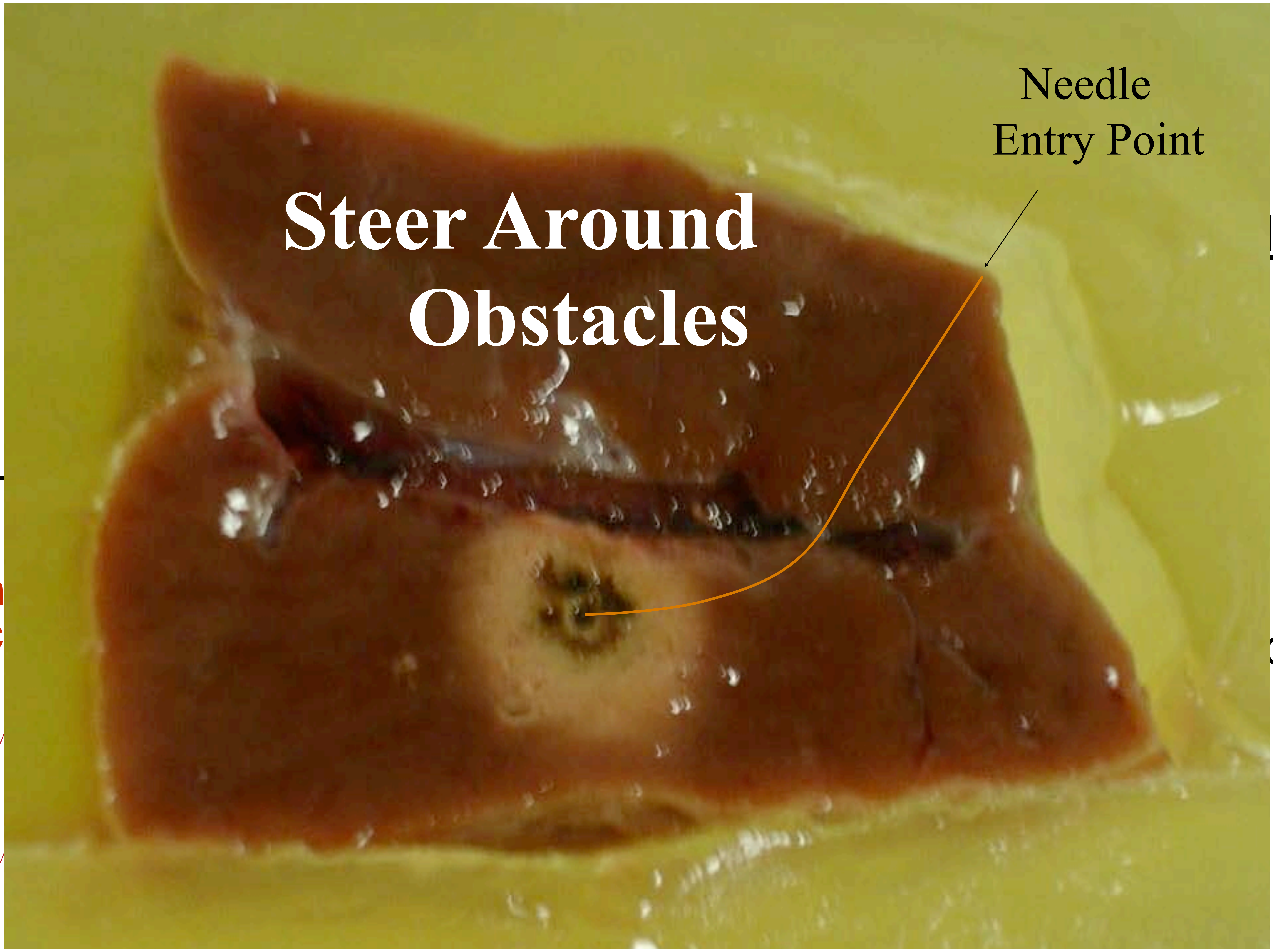
Skin

Layers
muscle
fat, etc.

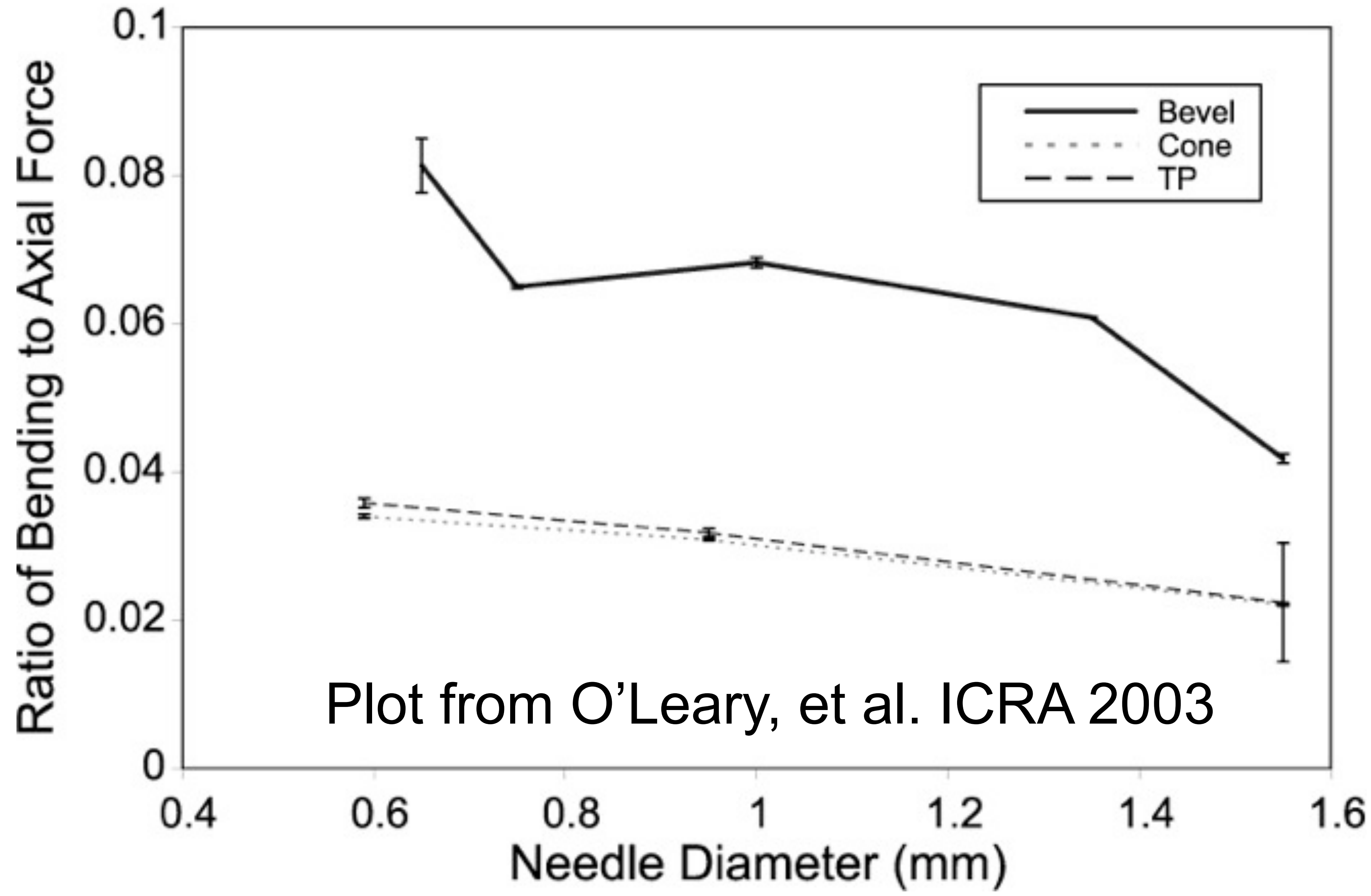
Organ
surfac

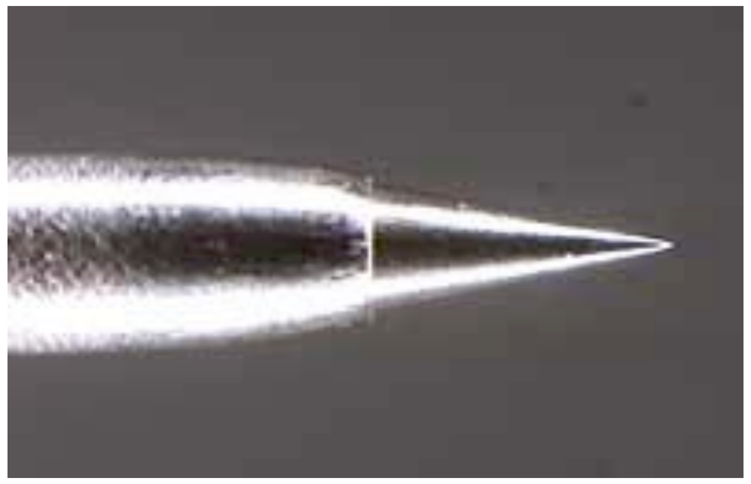
racy

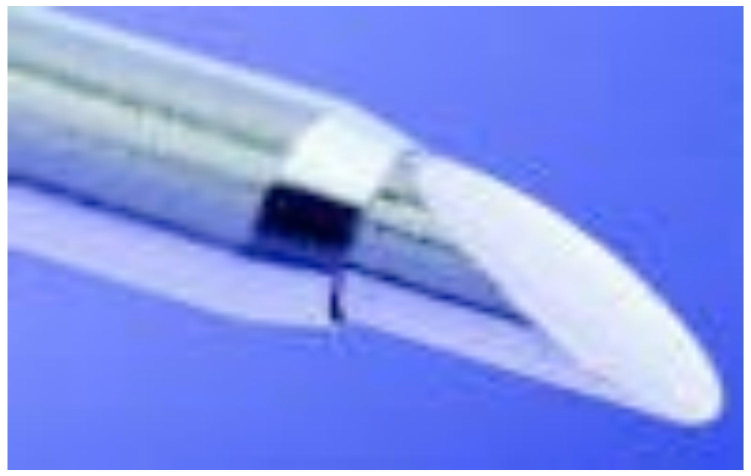
cts

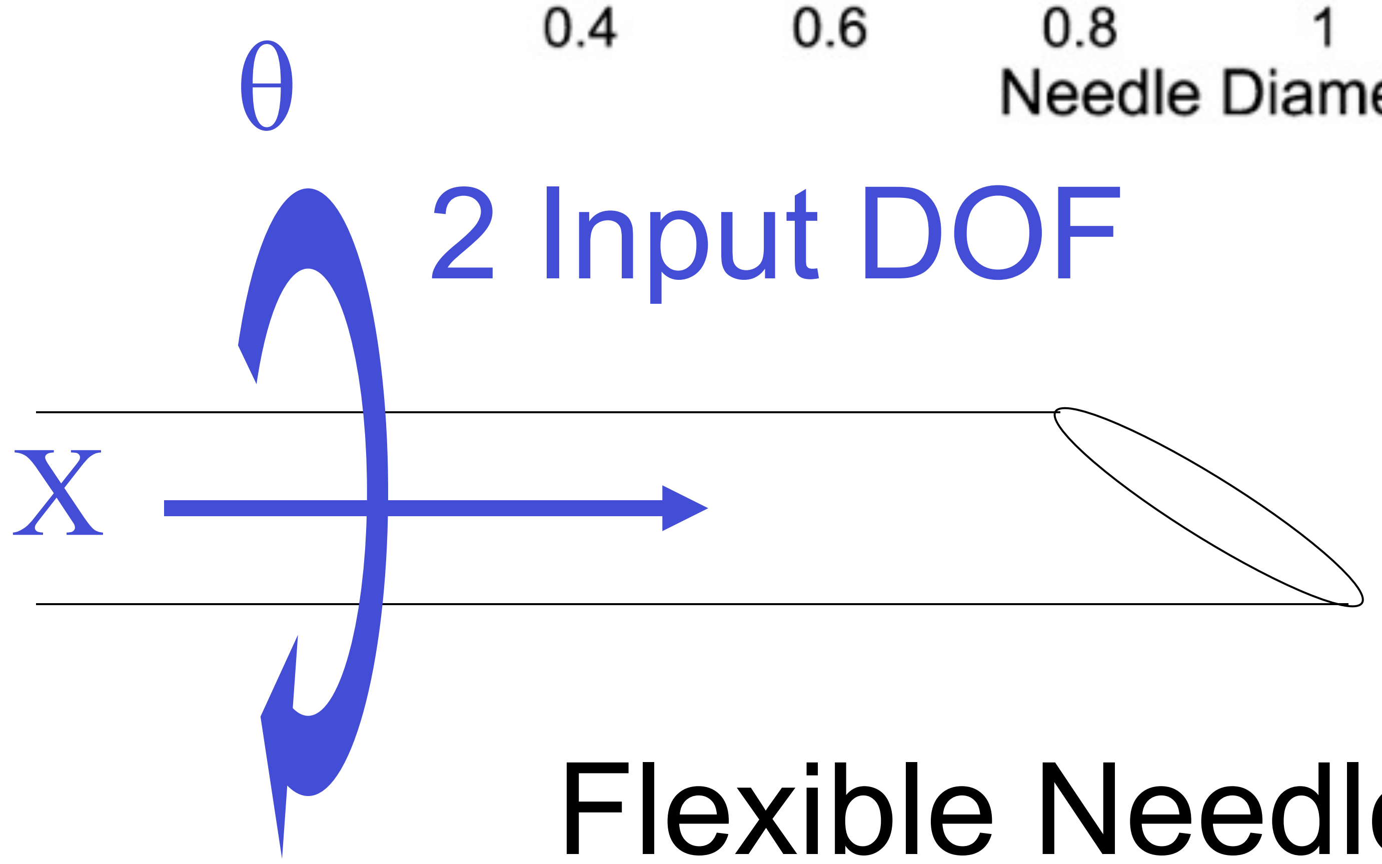


Harnessing Tip Asymmetry





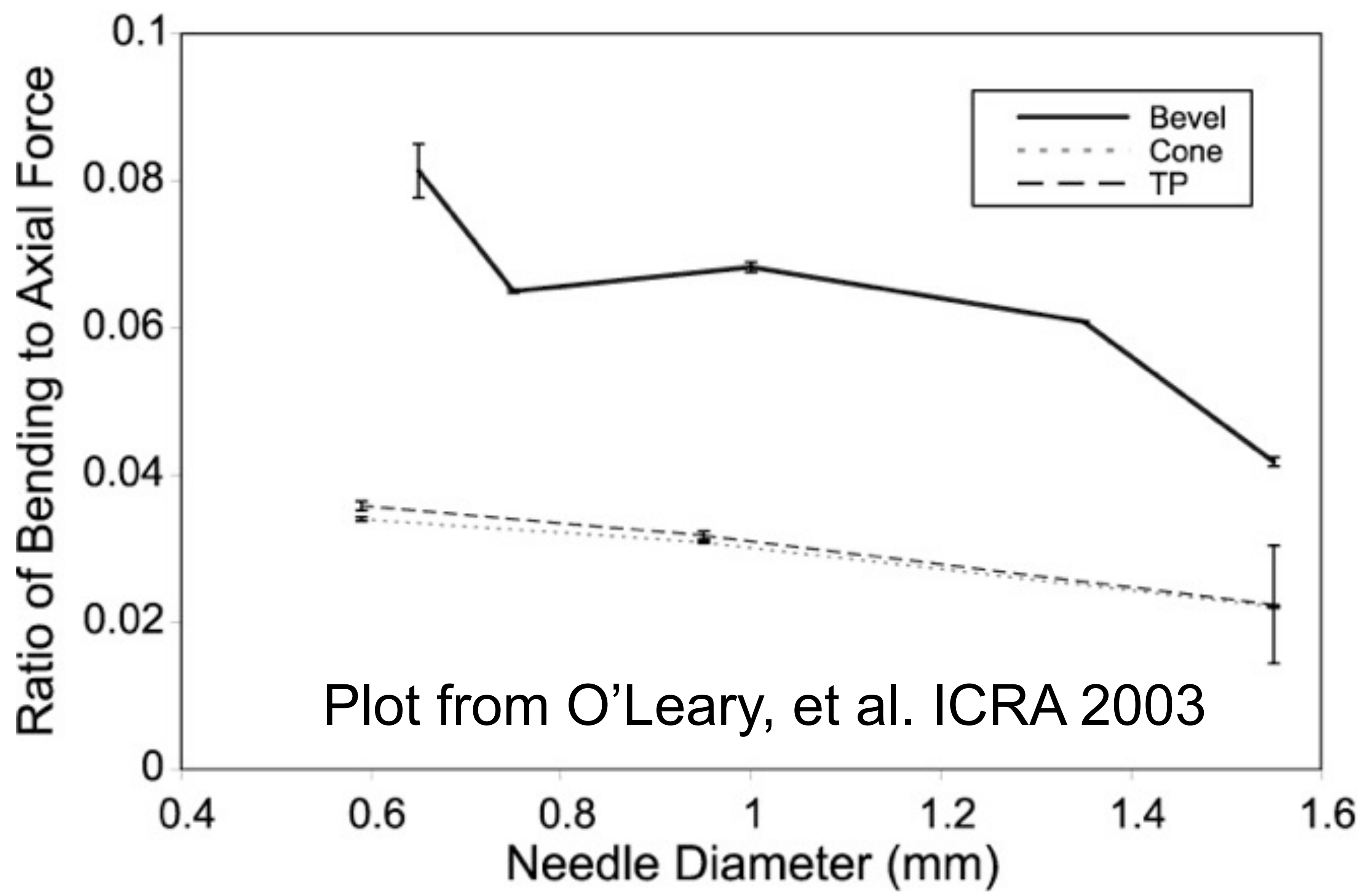


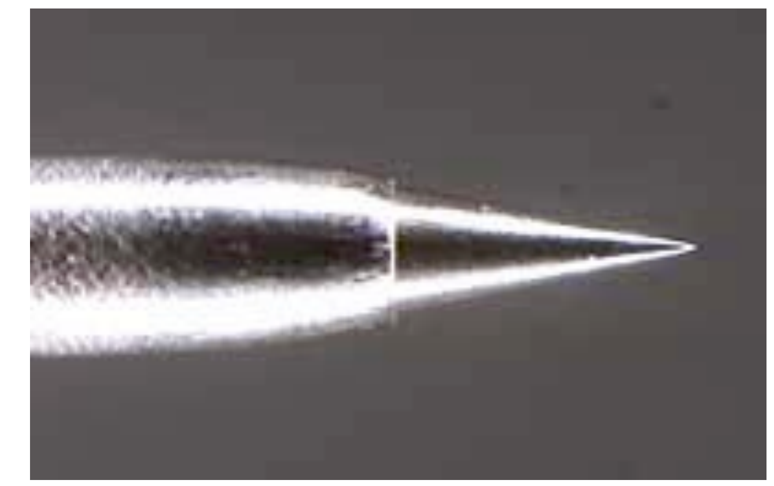


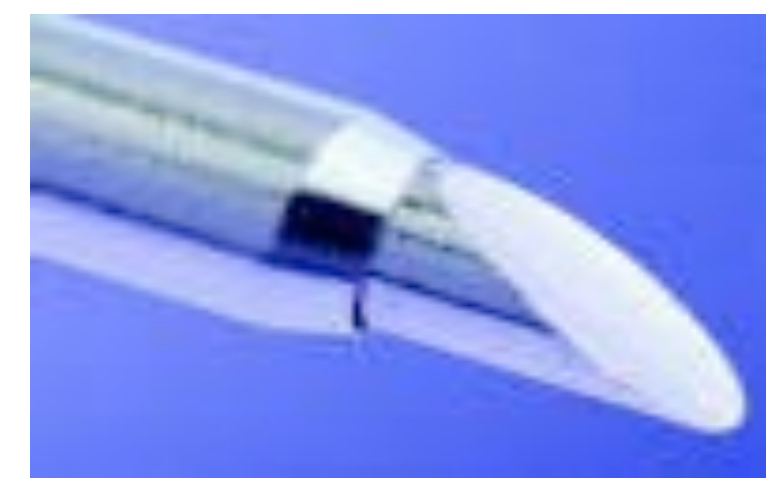
Flexible Needle
Asymmetric Tip

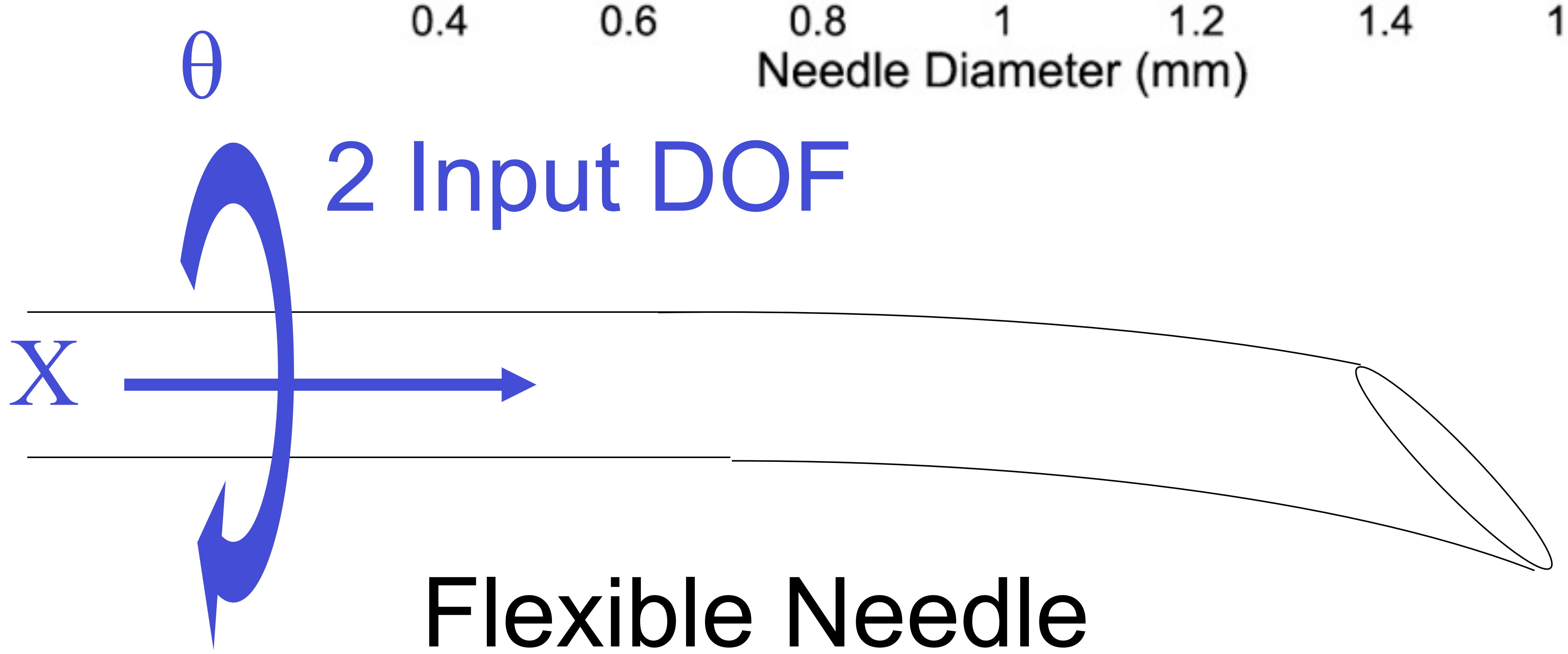
Target
6-DOF
Pose

Harnessing Tip Asymmetry





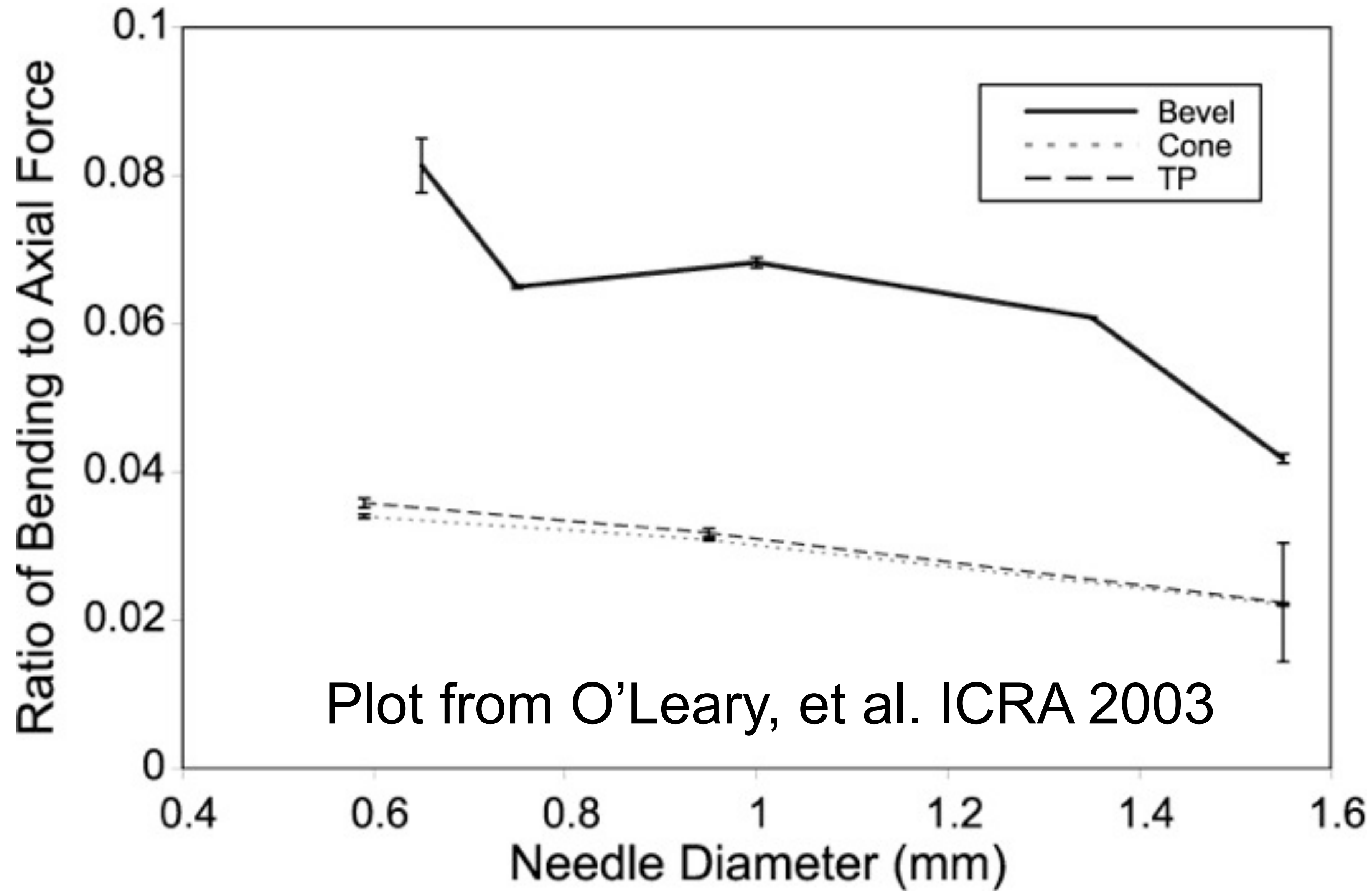


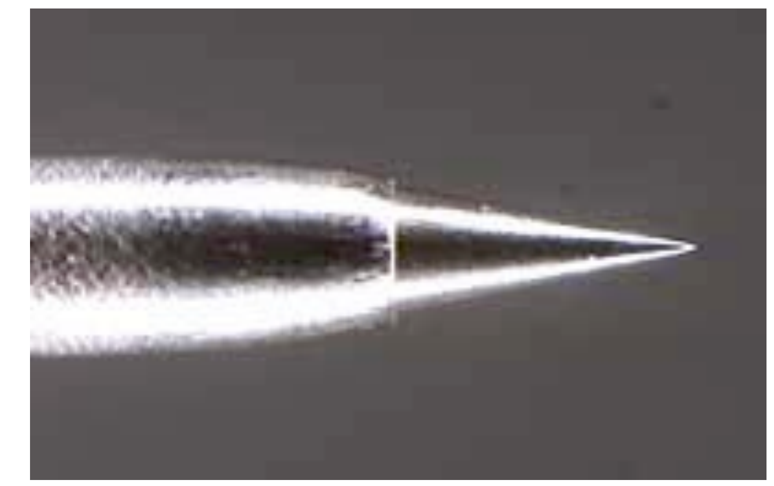


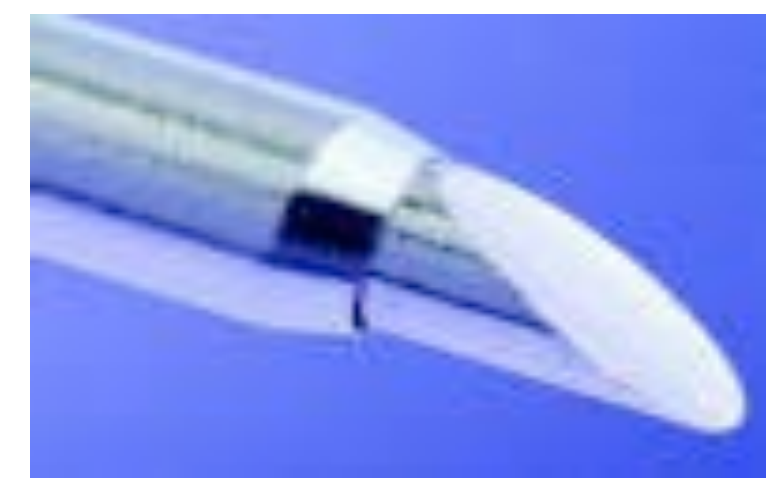
Flexible Needle
Asymmetric Tip

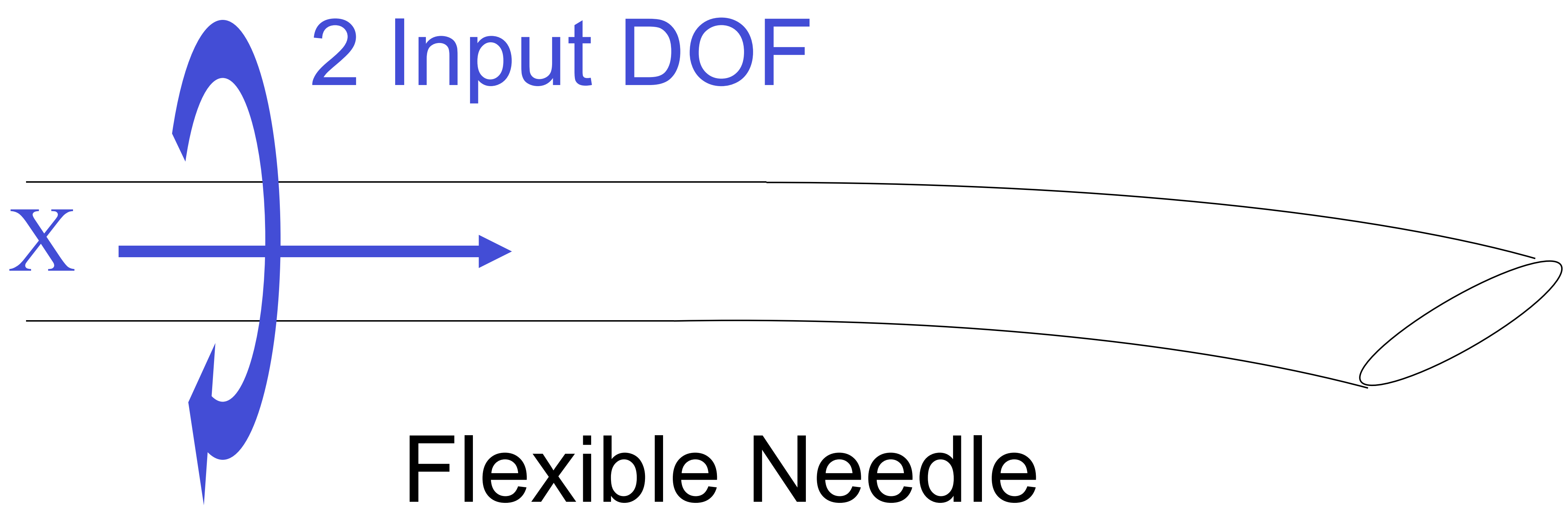
Target
6-DOF
Pose

Harnessing Tip Asymmetry







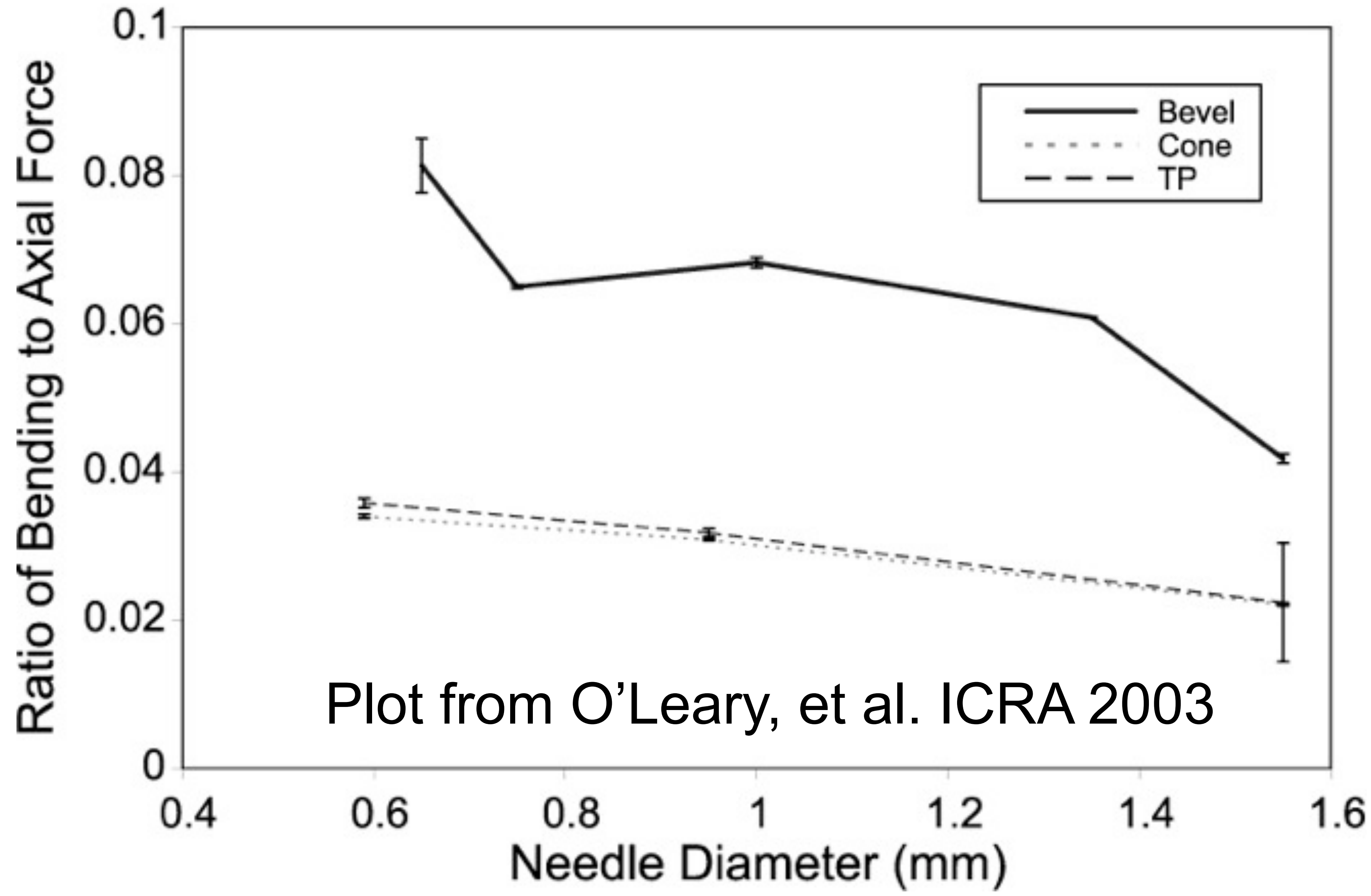


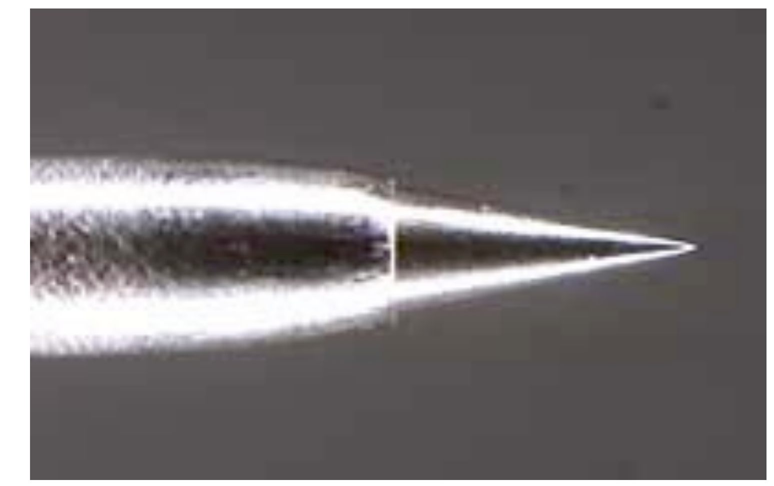
2 Input DOF

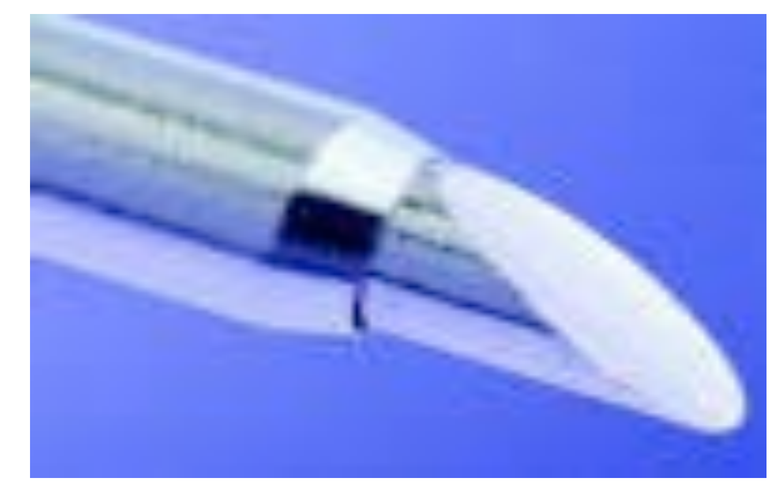
Flexible Needle
Asymmetric Tip

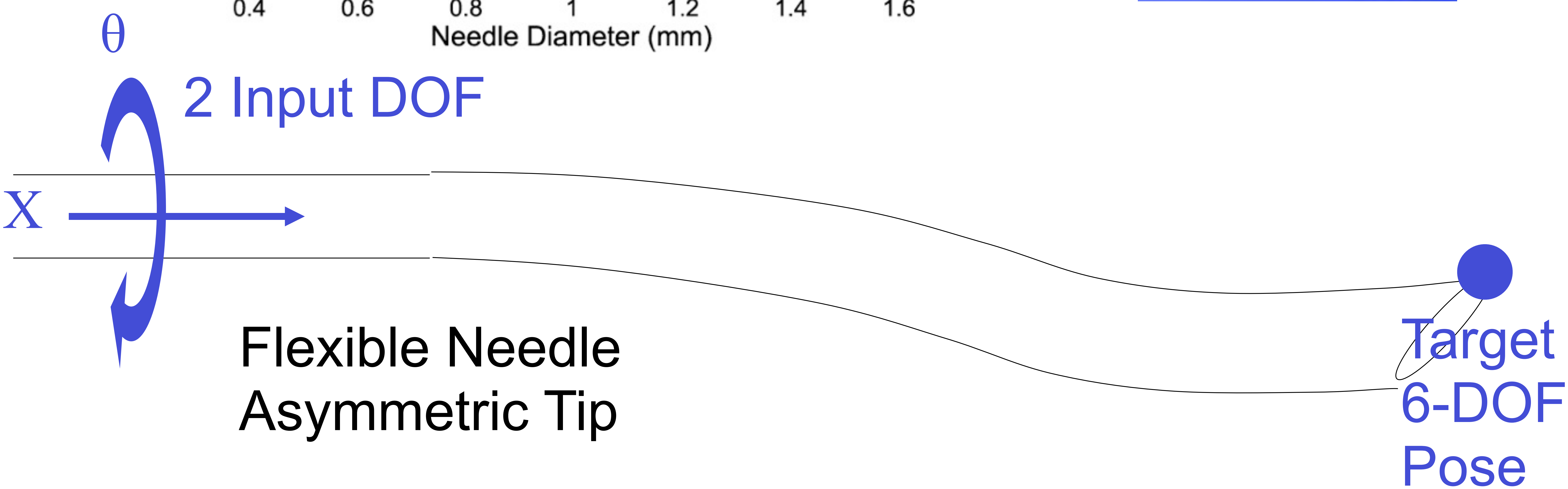
Target
6-DOF
Pose

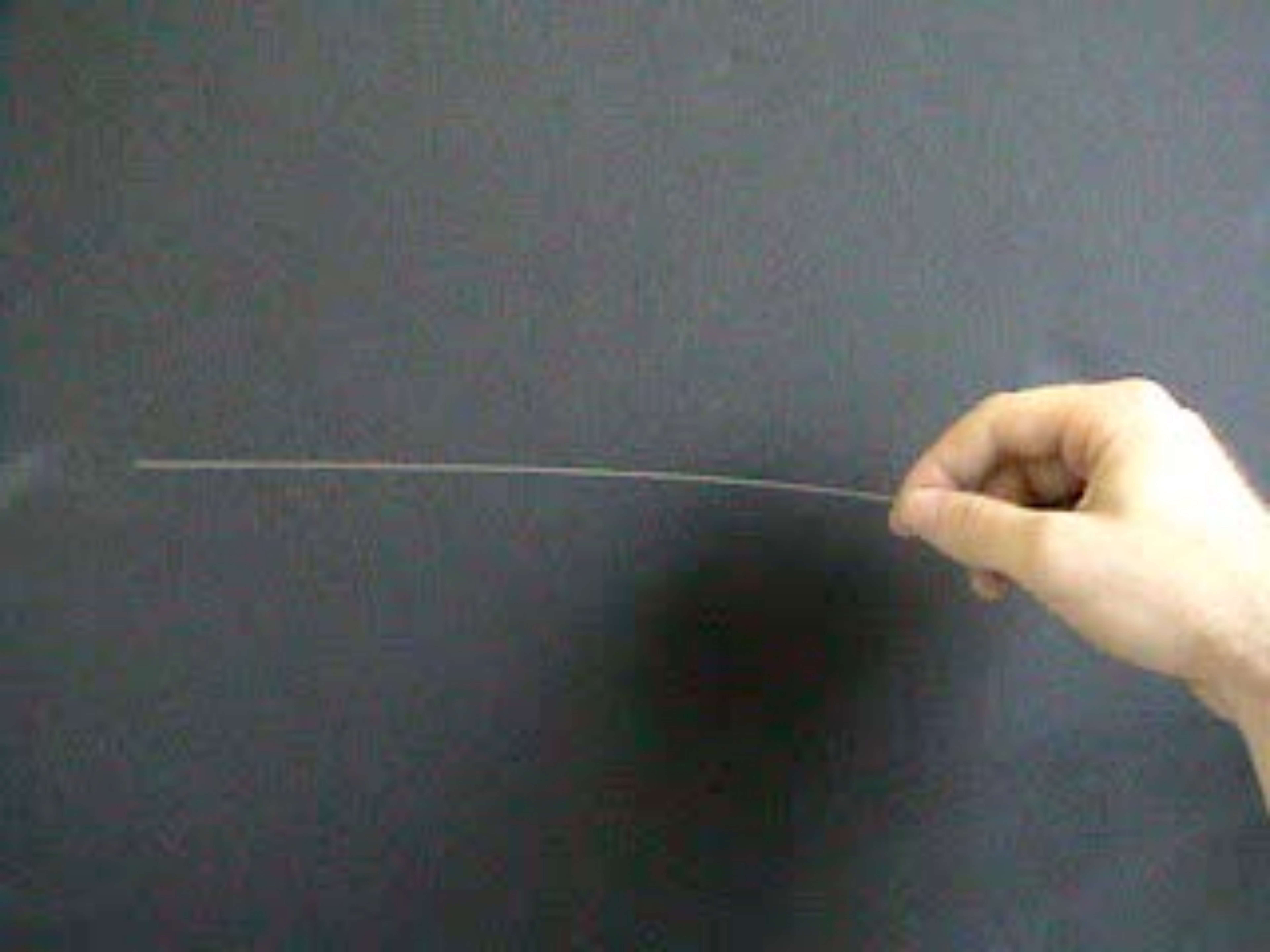
Harnessing Tip Asymmetry



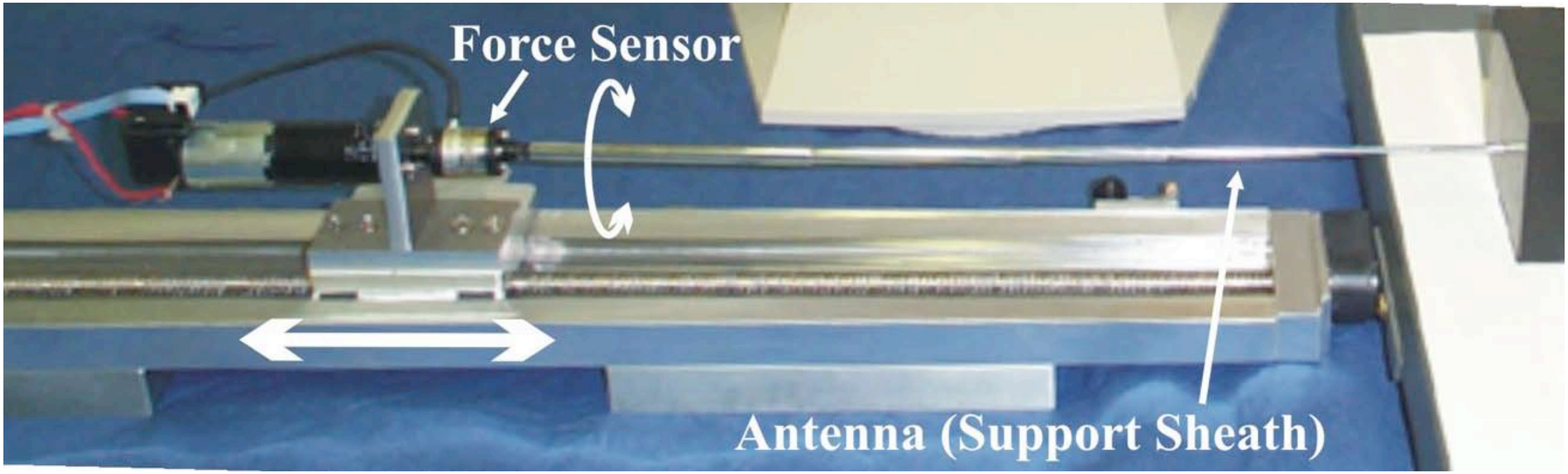






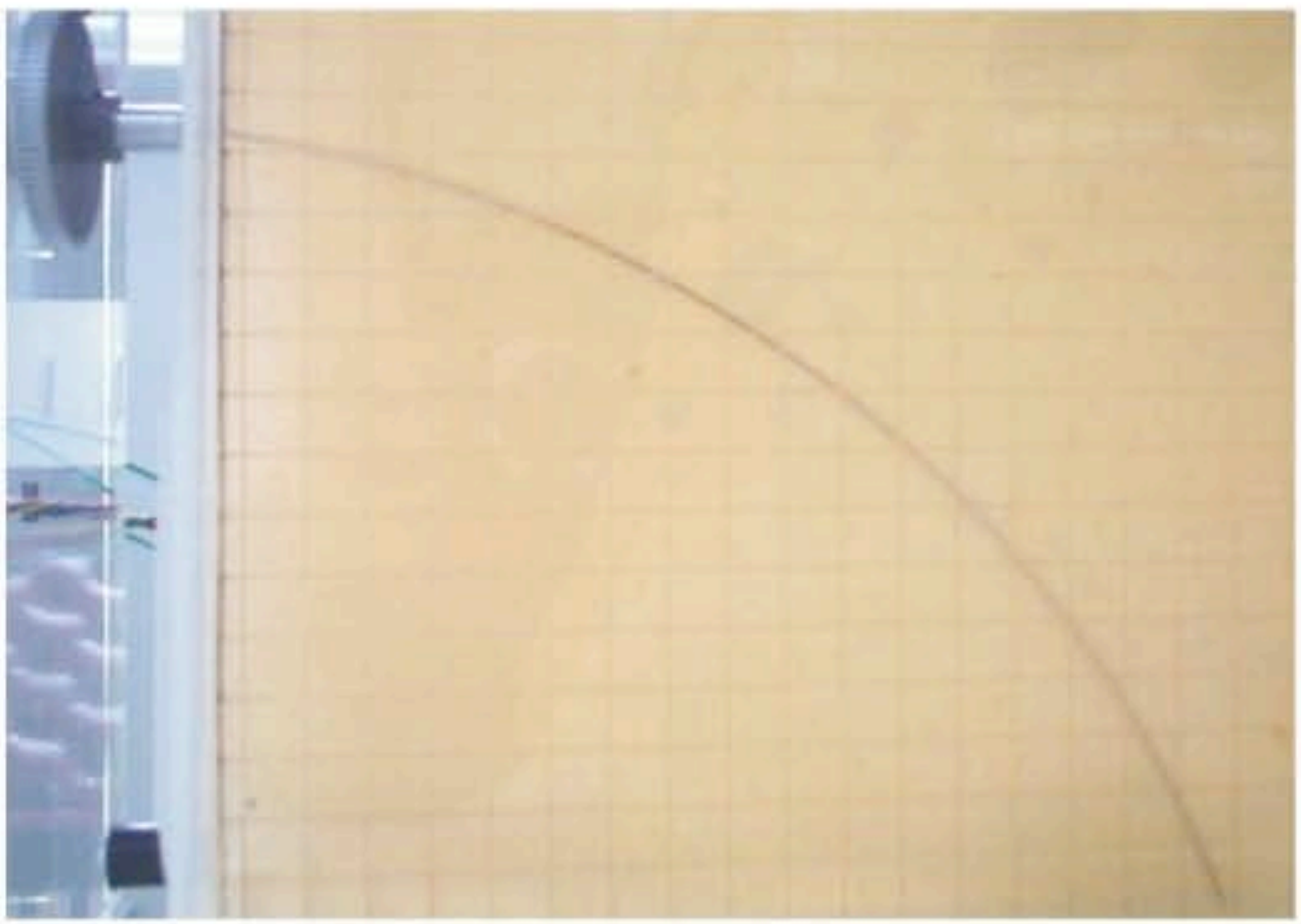


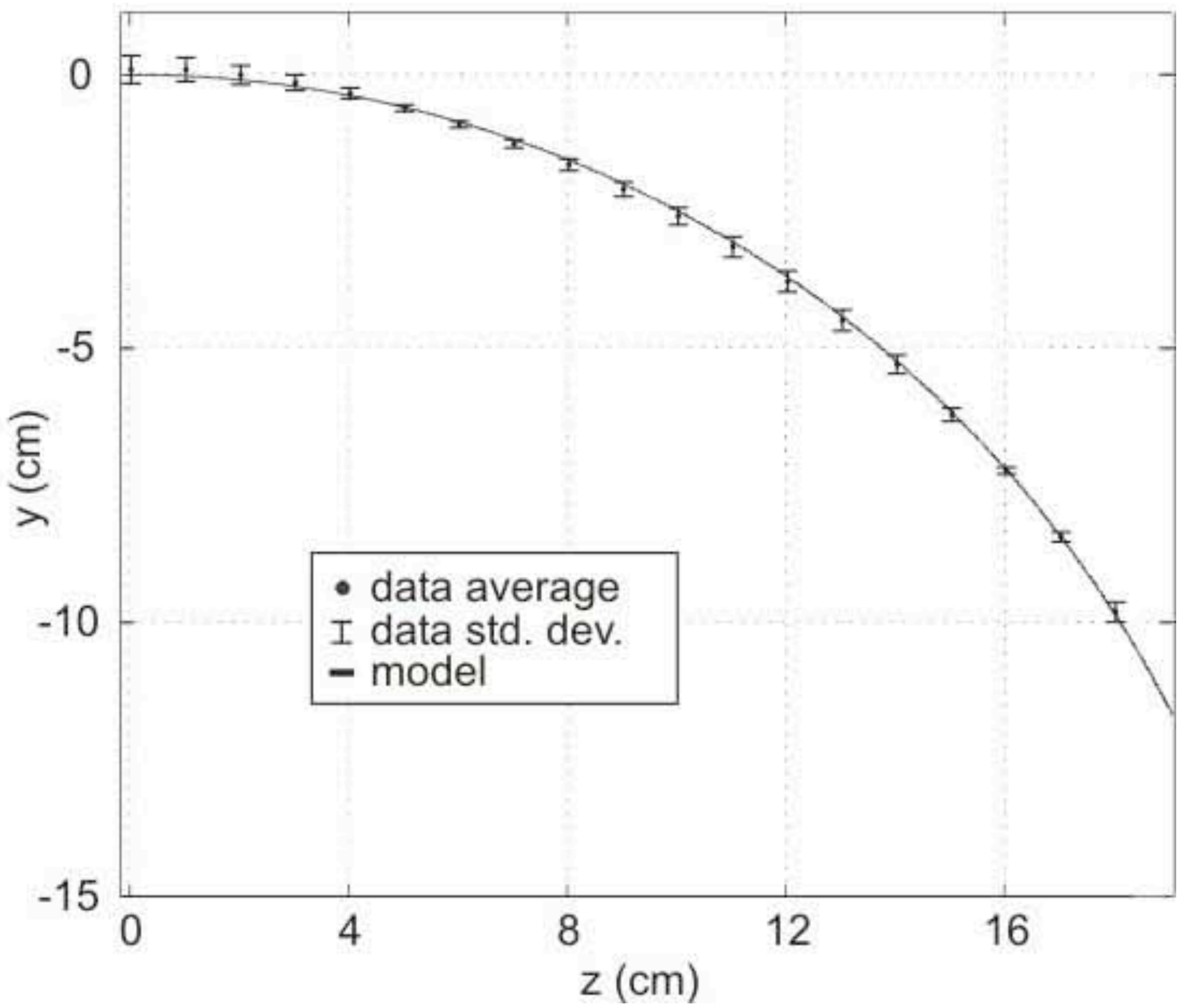
Robotic Flexible Needle Driver



R. J. Webster III, J. Memisevic, and A. M. Okamura. *Design Considerations for Robotic Needle Steering*. IEEE ICRA, 2005.

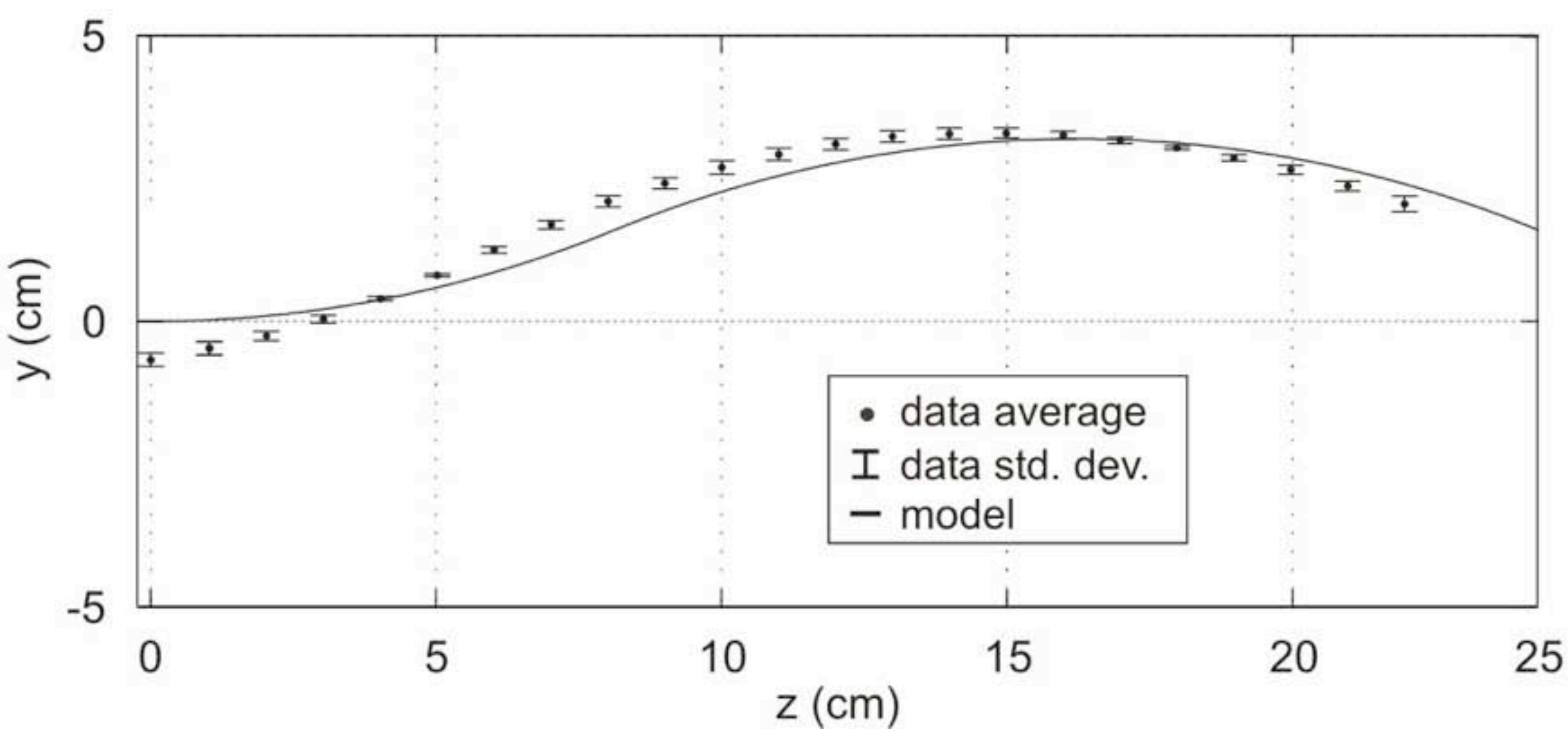
Is It Constant Curvature?





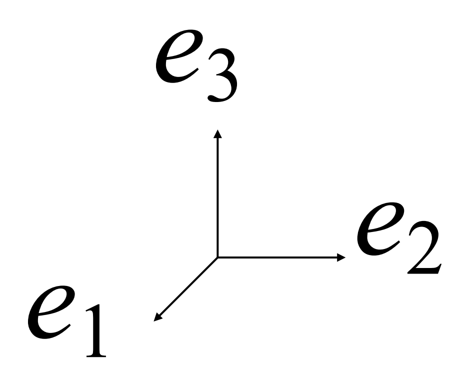
Looks good so far ...

Is It Constant Curvature?

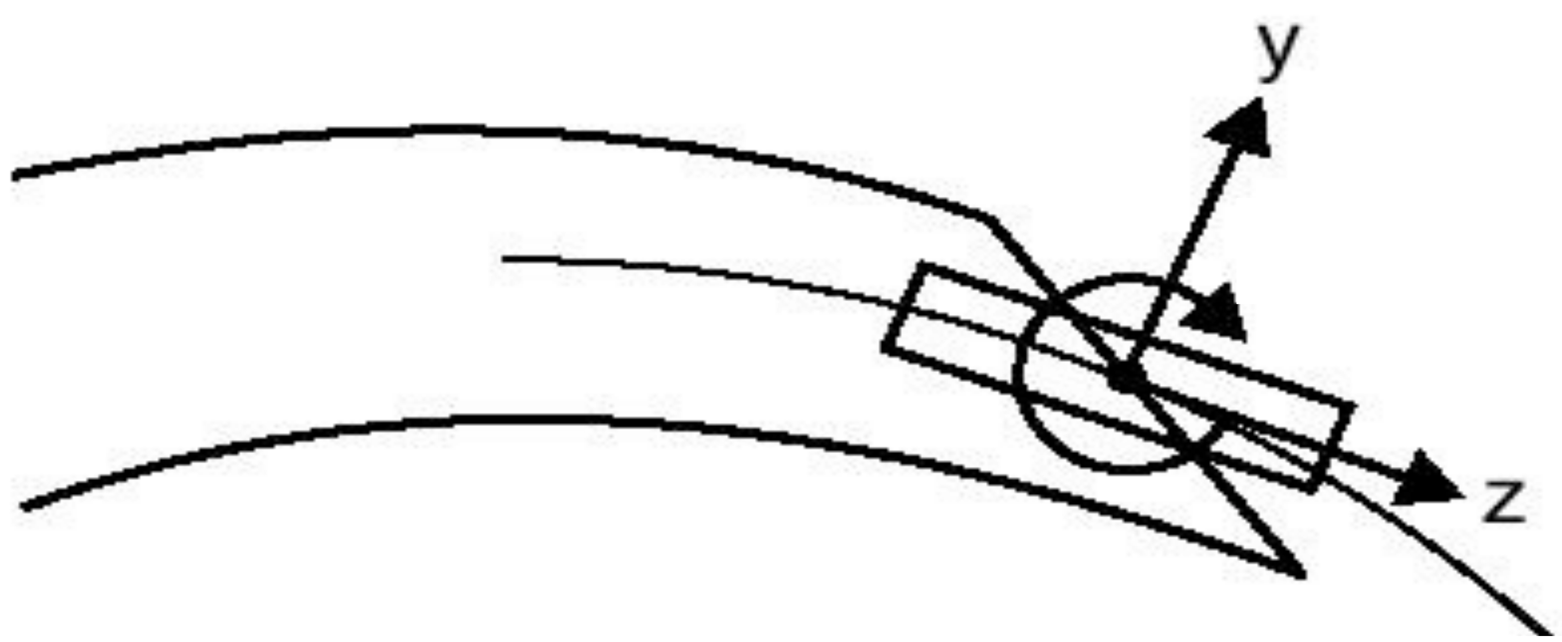


Not really ... but maybe not too far off?

Needle Kinematic Modeling



Unicycle

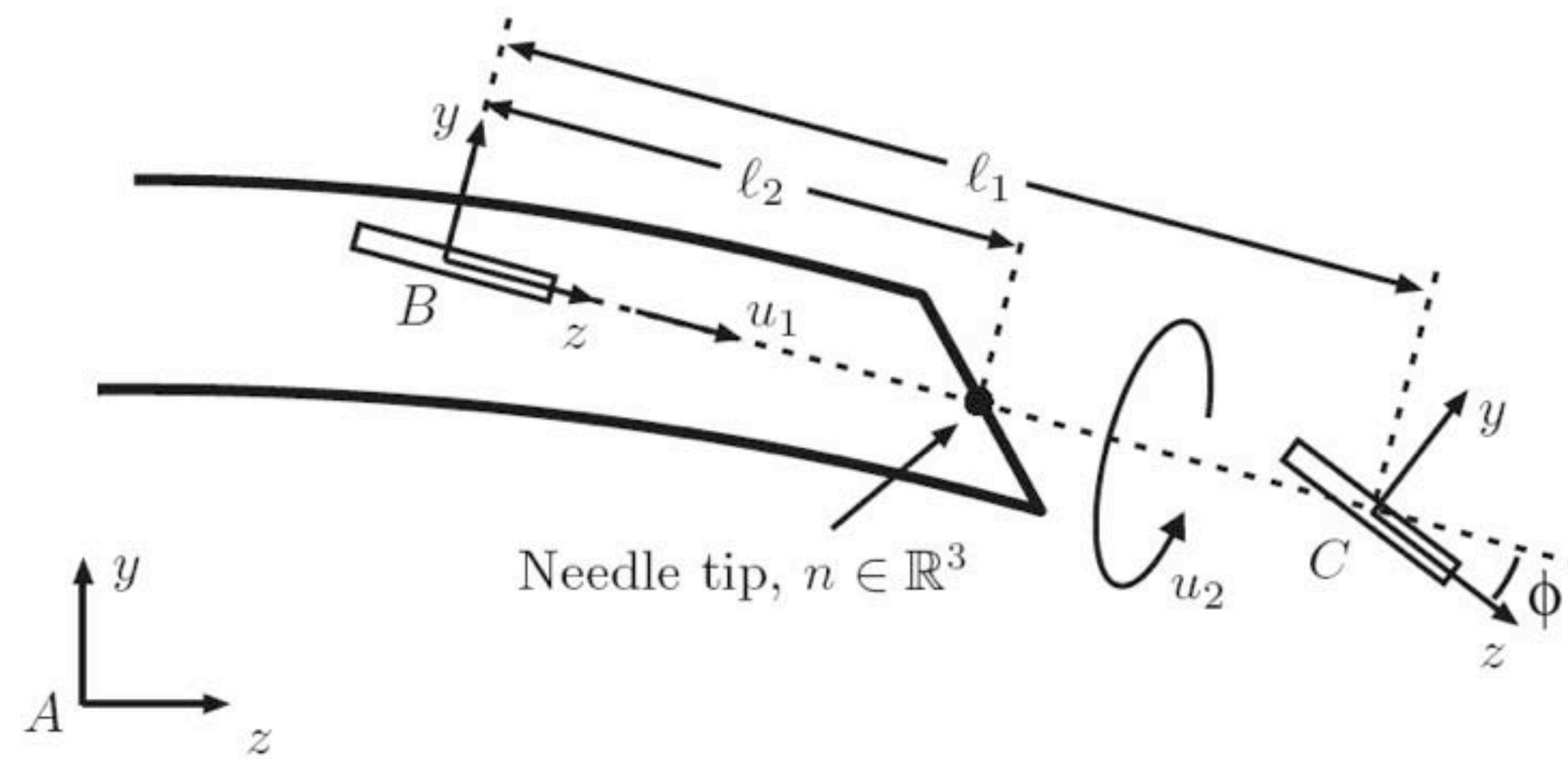


$$e_1^T v_{ab}^b = e_2^T v_{ab}^b = e_2^T \omega_{ab}^b = 0$$

$$\frac{1}{\kappa} e_1^T \omega_{ab}^b = e_3^T v_{ab}^b$$

One Parameter: κ

Bicycle

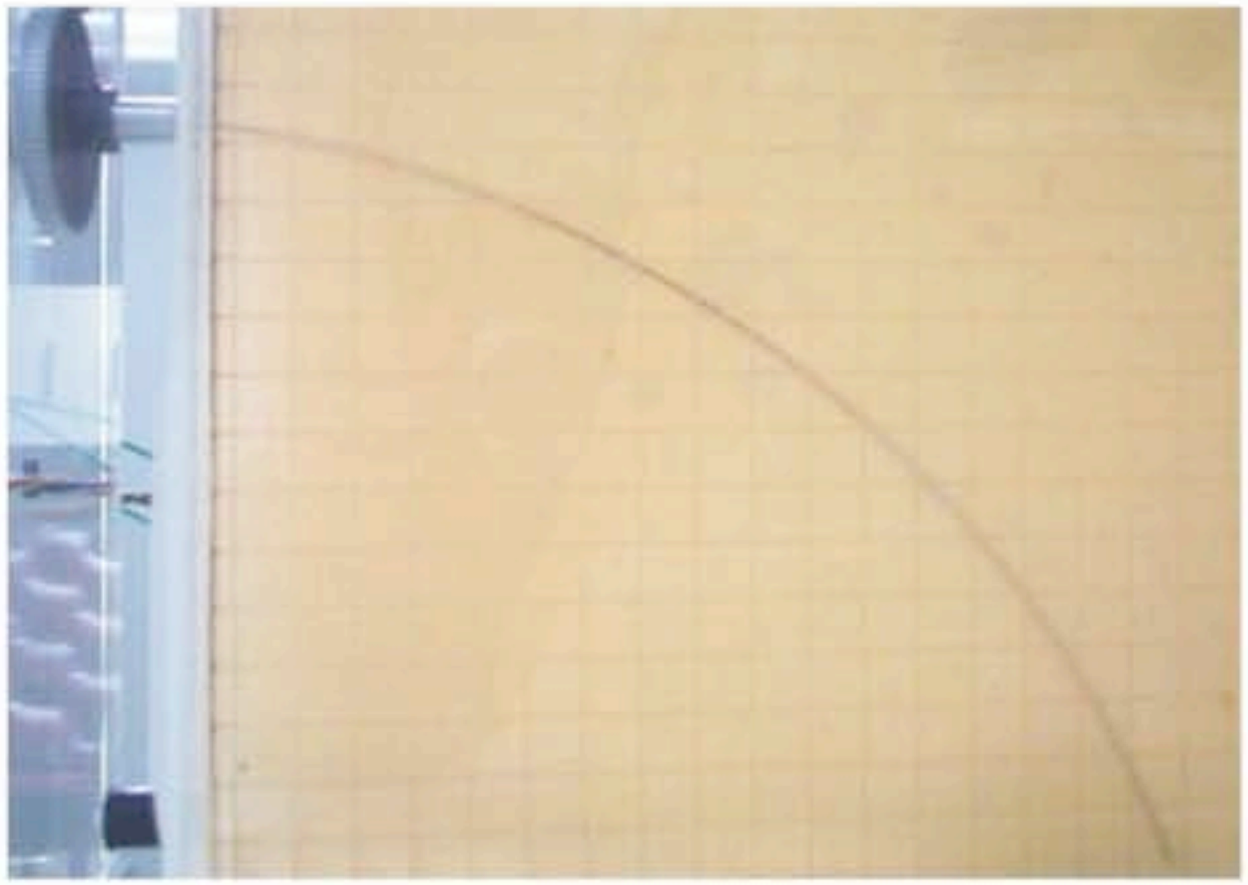


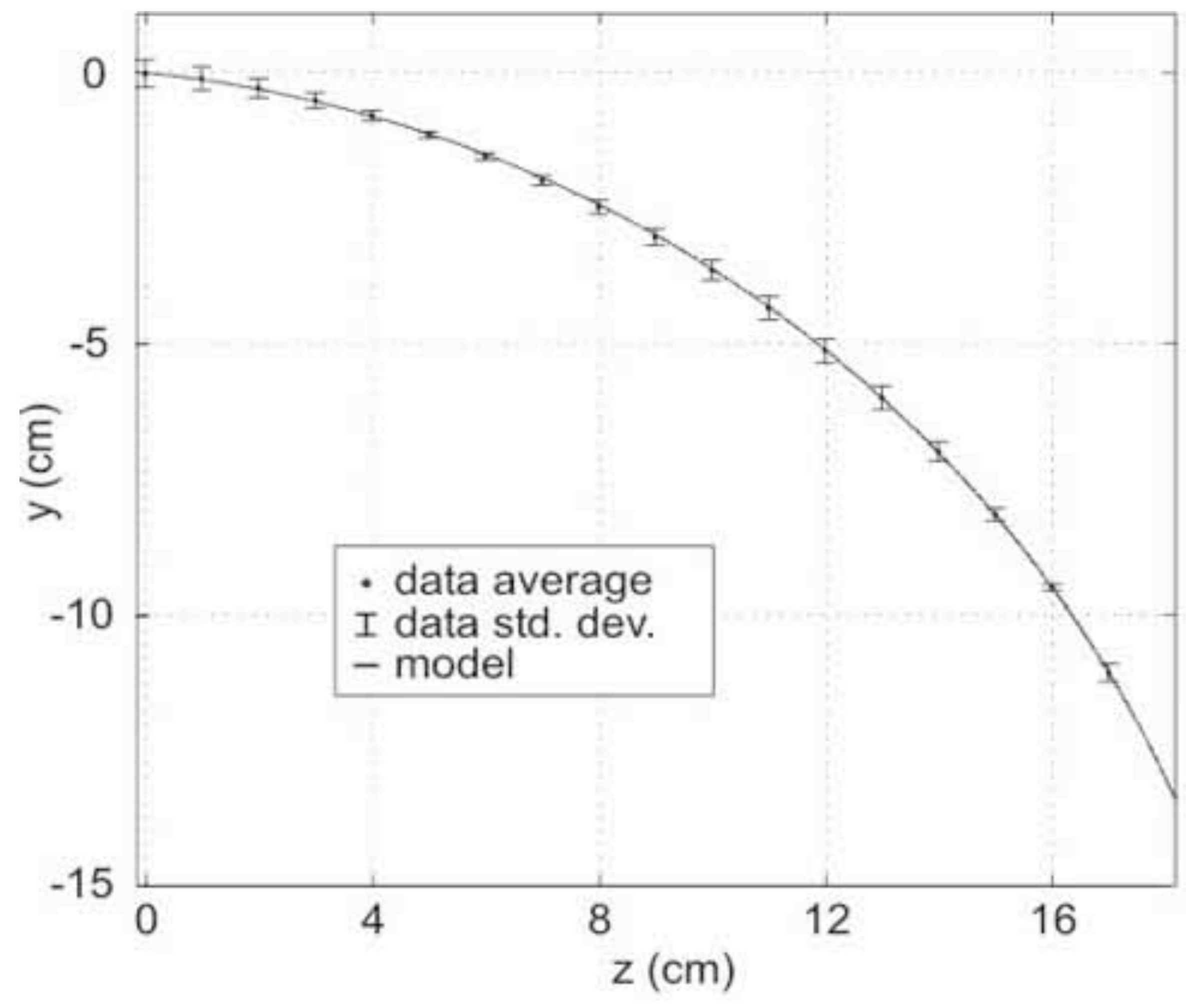
$$e_1^T v_{ab}^b = e_2^T v_{ab}^b = e_1^T v_{ac}^b = e_2^T v_{ac}^b = 0$$

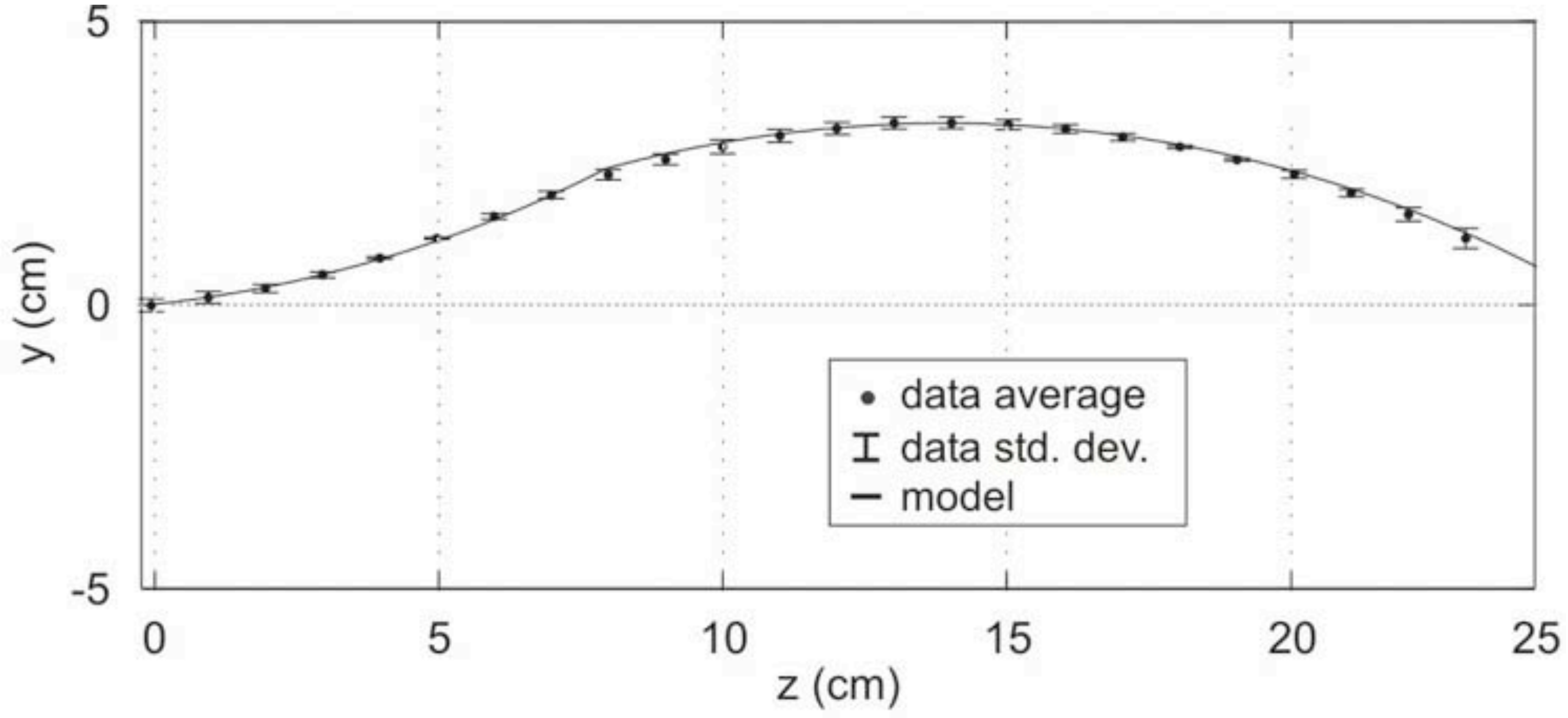
Two Parameters κ, l_2

Webster, Kim, Cowan, Chirikjian, and Okamura, “Nonholonomic Modeling of Needle Steering,” IJRR, 25(5–6), 2006.

Bicycle Results

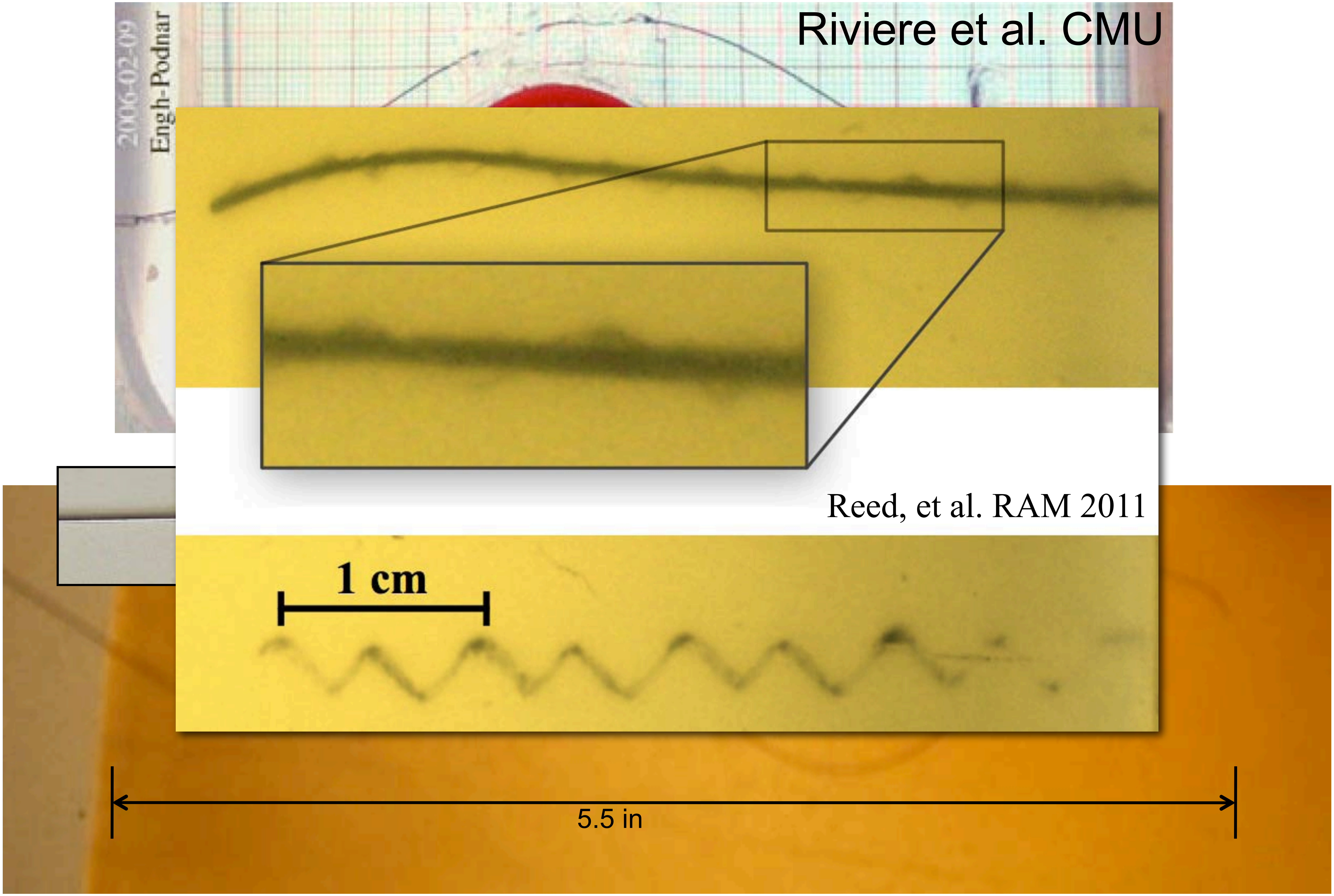




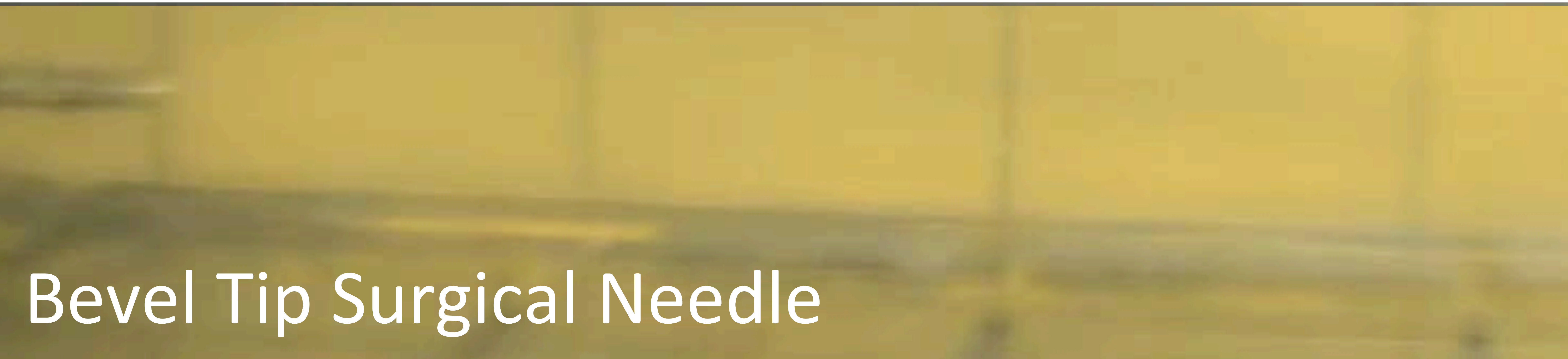


Webster, Kim, Cowan, Chirikjian, and Okamura, “Nonholonomic Modeling of Needle Steering,” IJRR, 25(5–6), 2006.

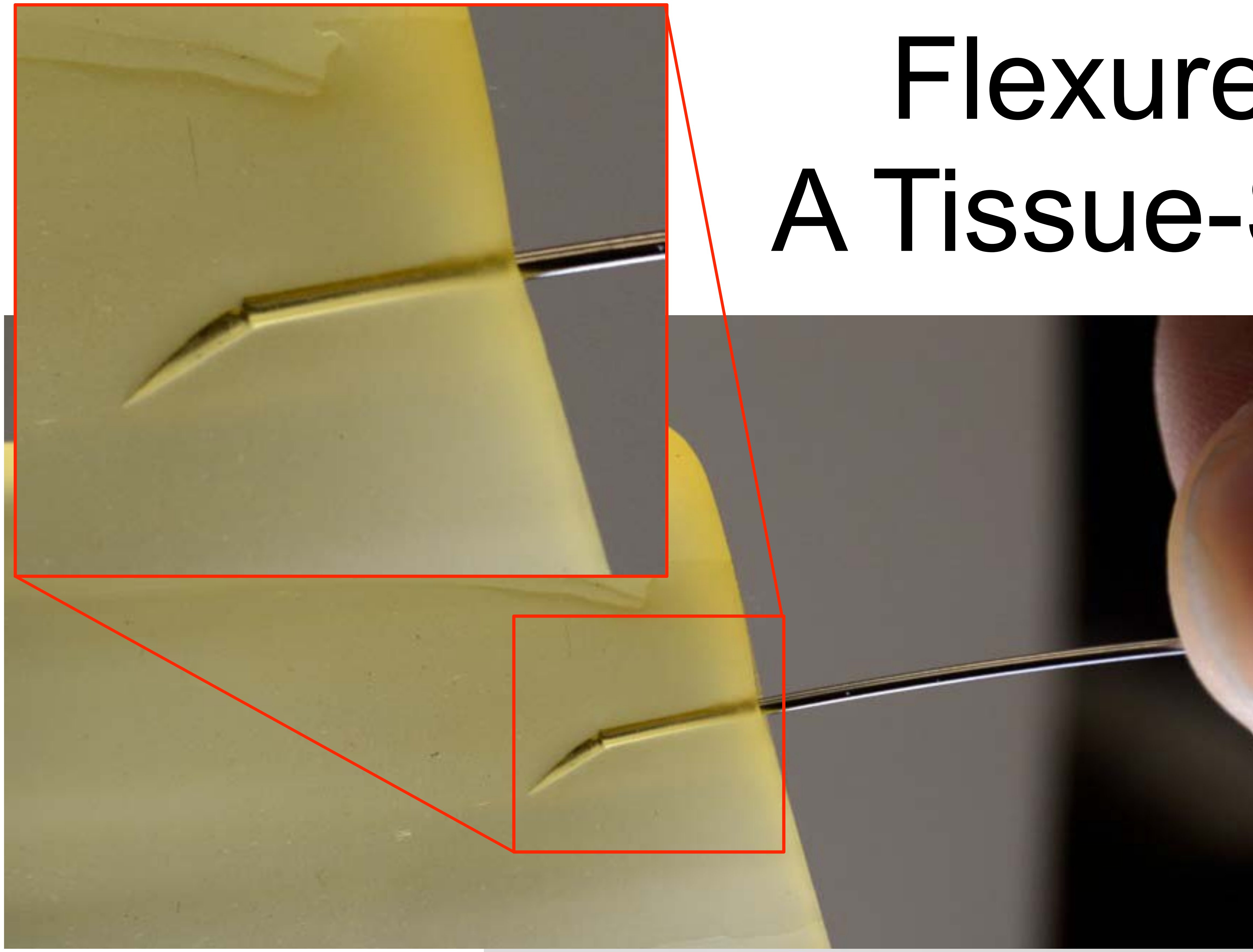
Needle Tip Design

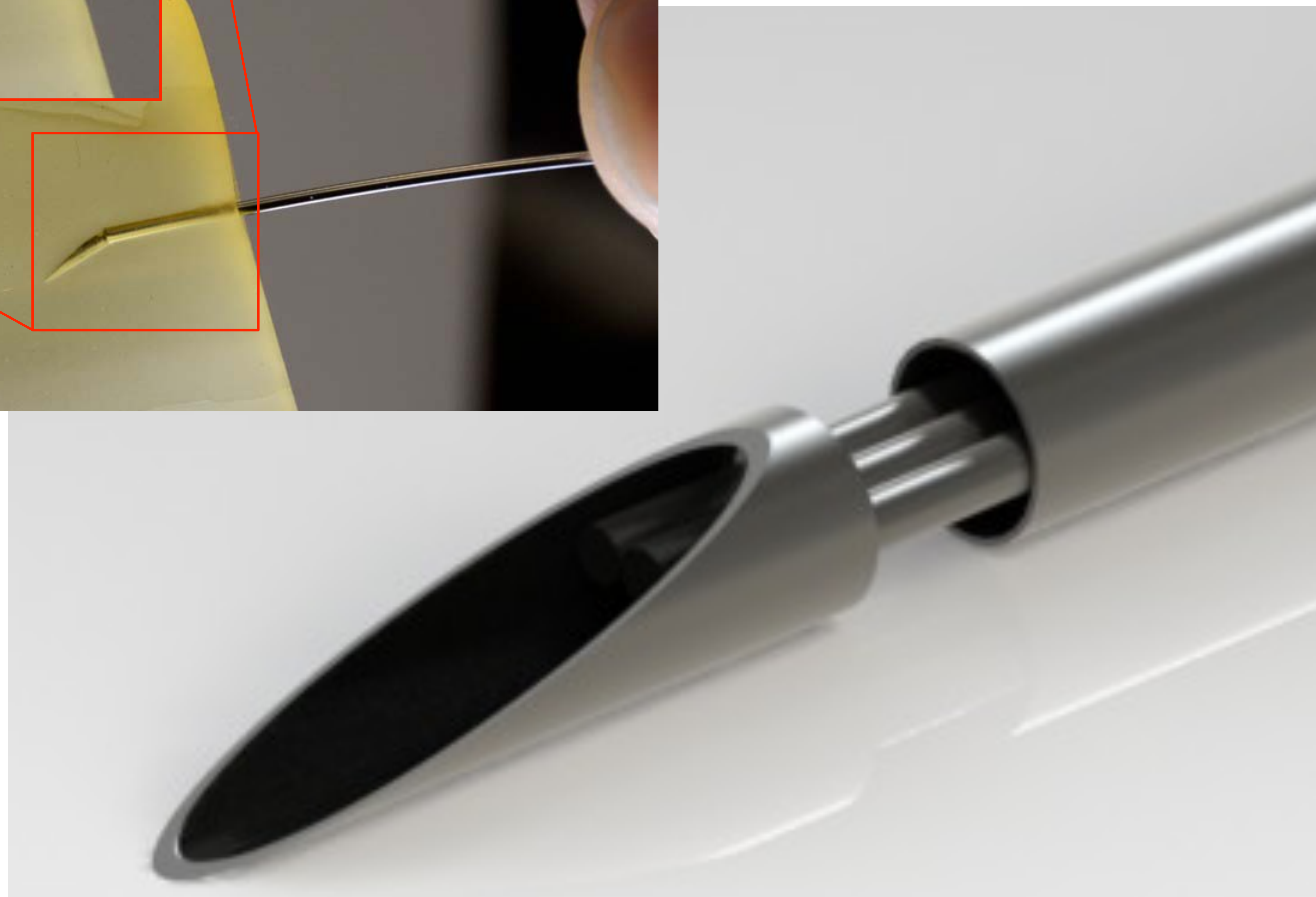


Duty Cycling: Tissue Damage



Flexure Tip Needle: A Tissue-Sparing "Kink"!

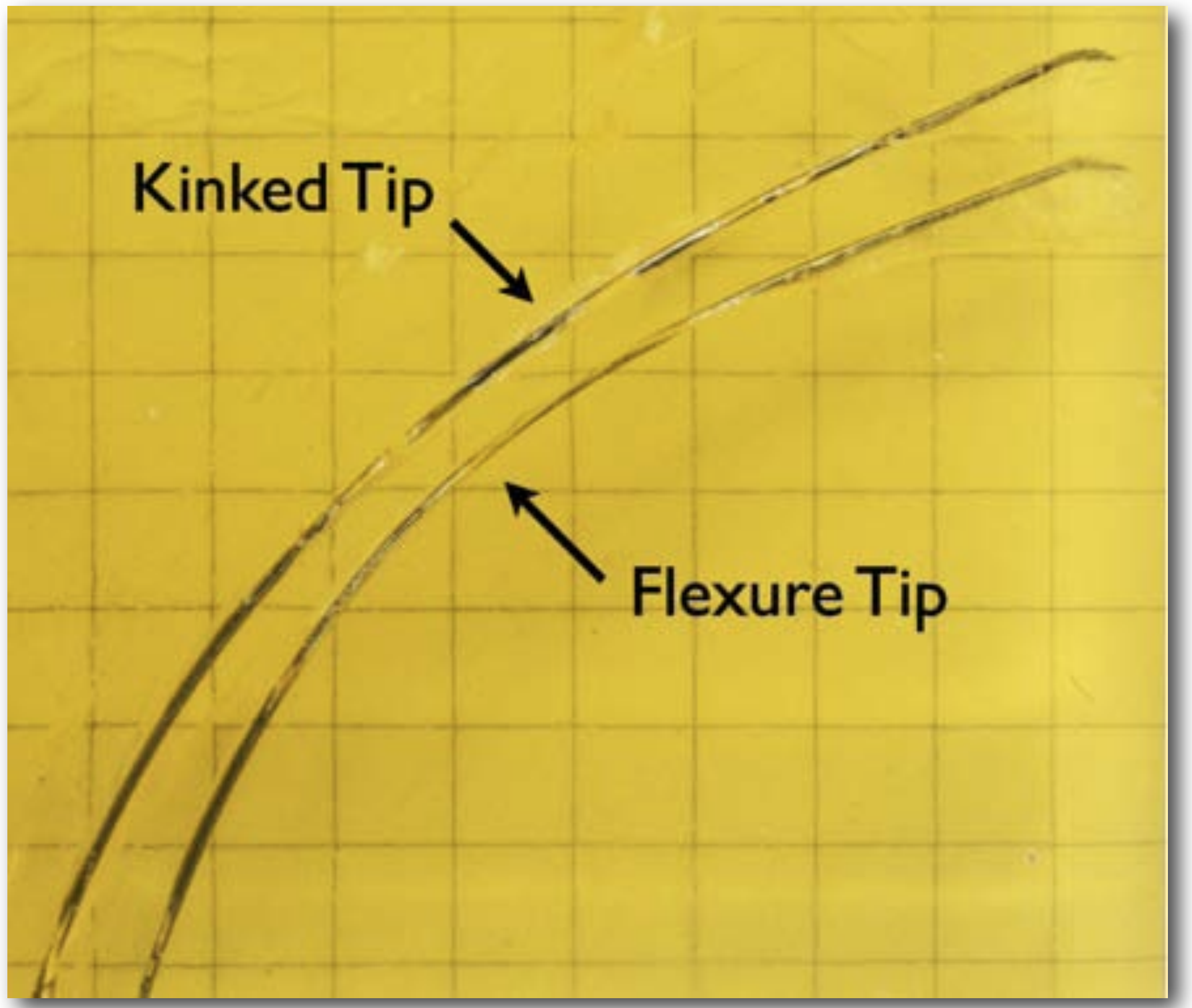




Swaney, Burgner, Gilbert, and Webster, "A Flexure-Based Steerable Needle: High Curvature with Reduced Tissue Damage," TBME 2013.

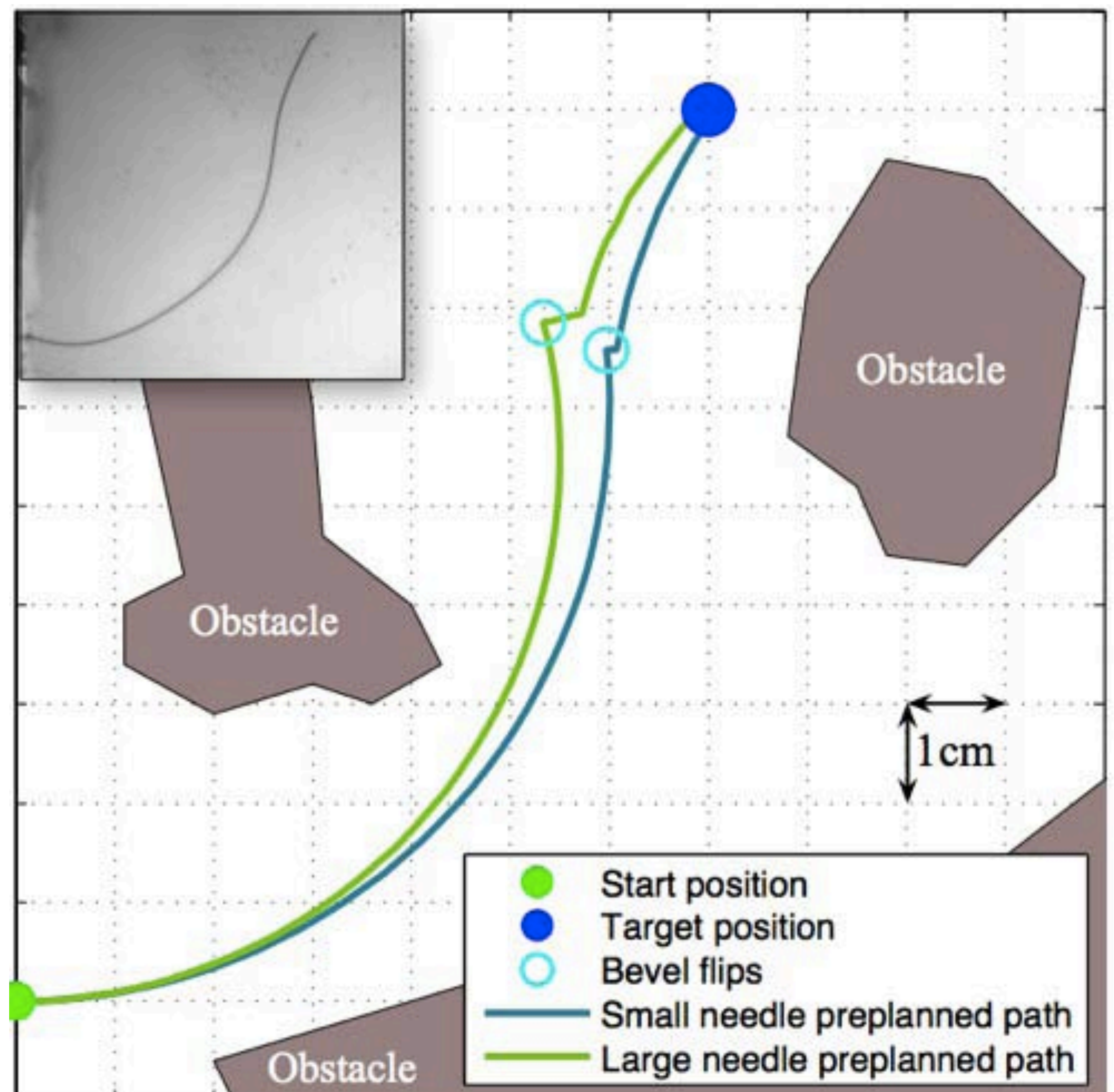
Flexure Tip Steerable Needle

- Reduced Tissue Damage
- Max curvature same as kinked tip



Bevel Tip Surgical Needle

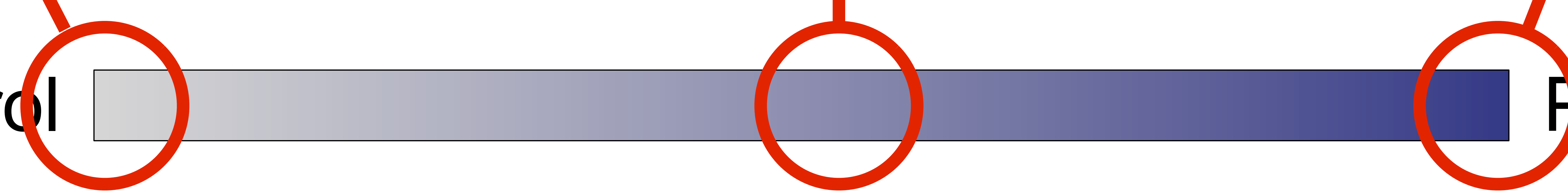
Control: How Can We Drive the Needle to a Desired Location?



Reed, et al. "Robot-Assisted Needle Steering," IEEE RAM 18(4), pp. 35-46, Dec. 2011.

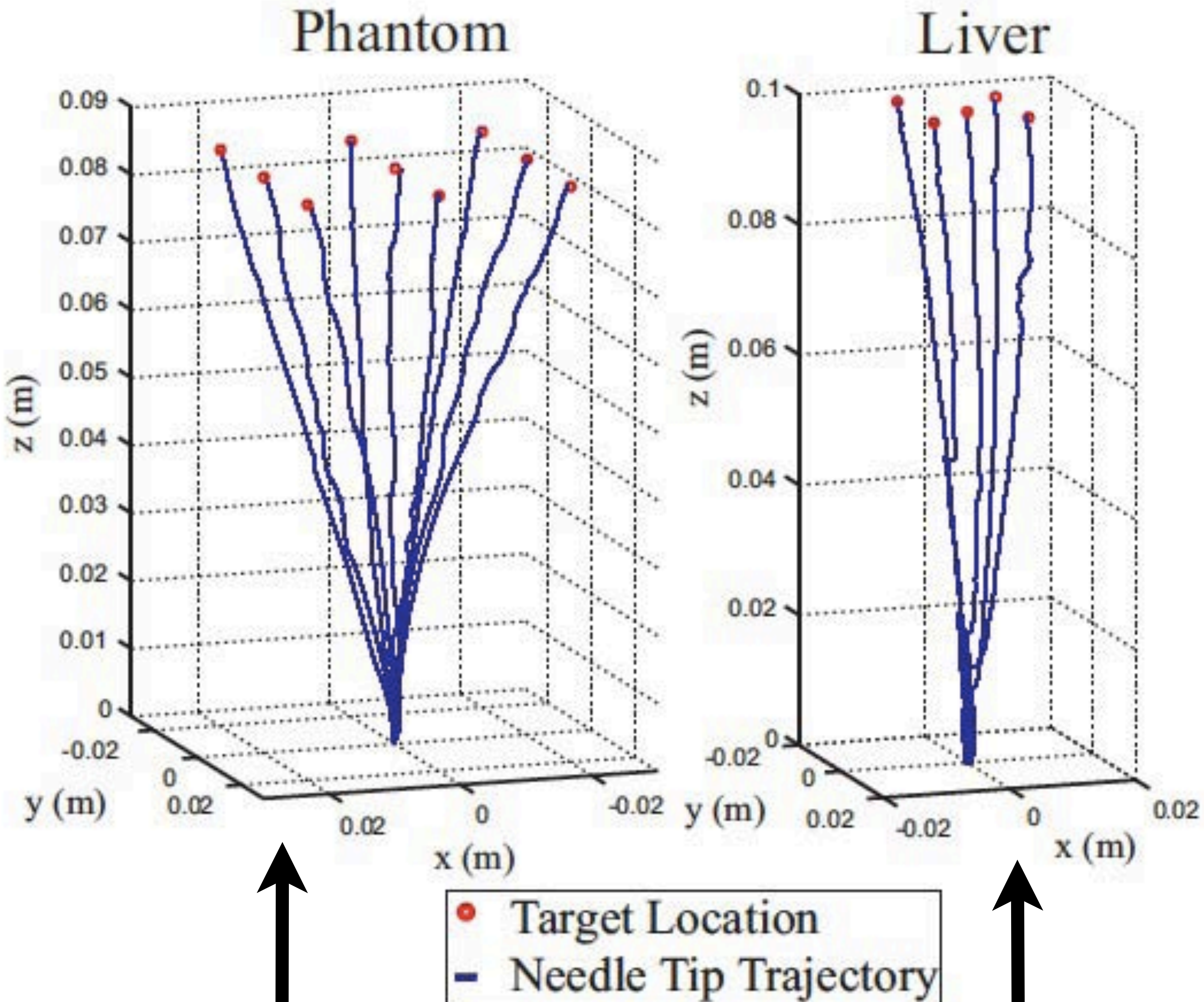
Can we do this in 3D?

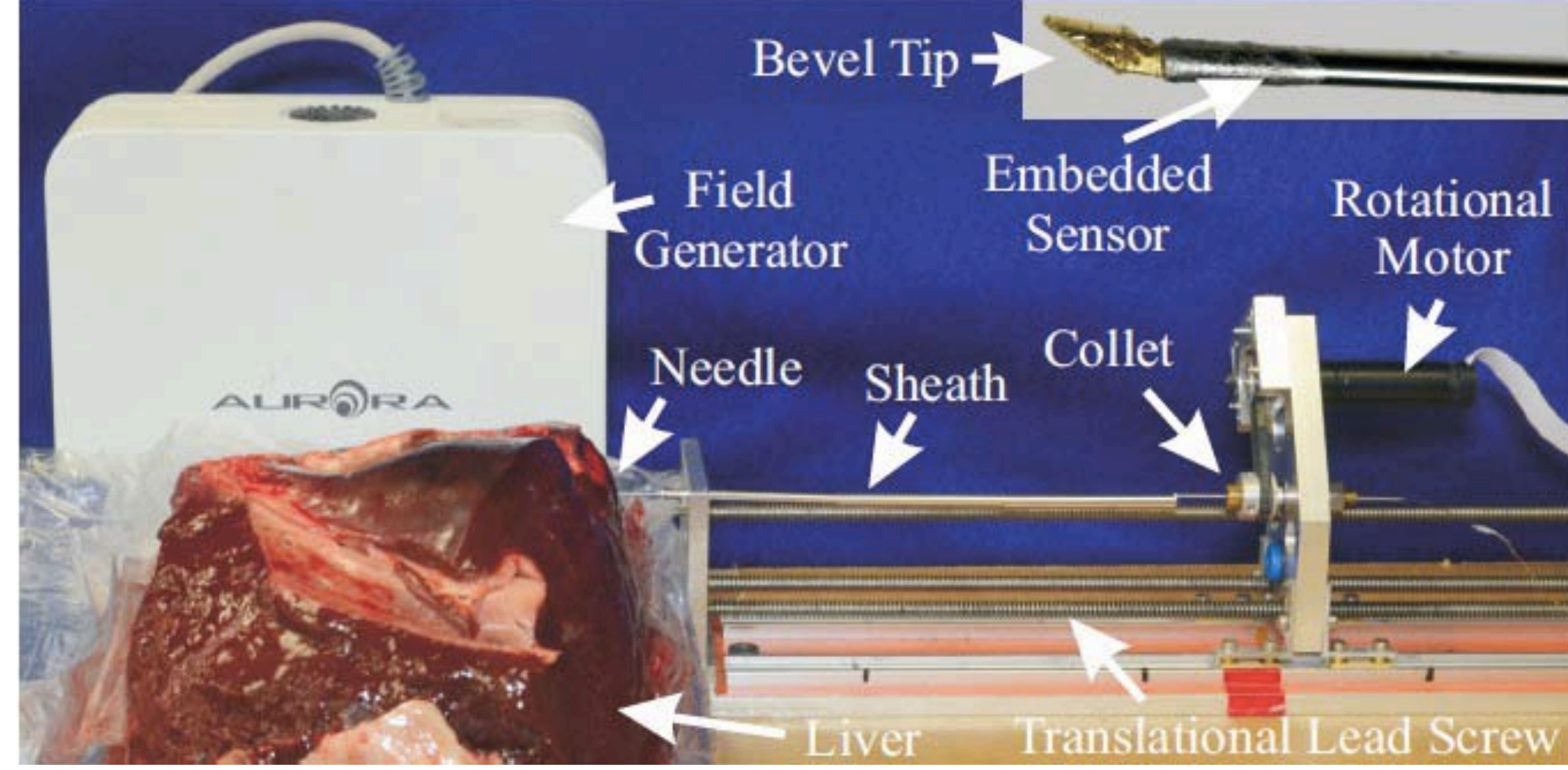
Can we do this (in 3D) fast enough?



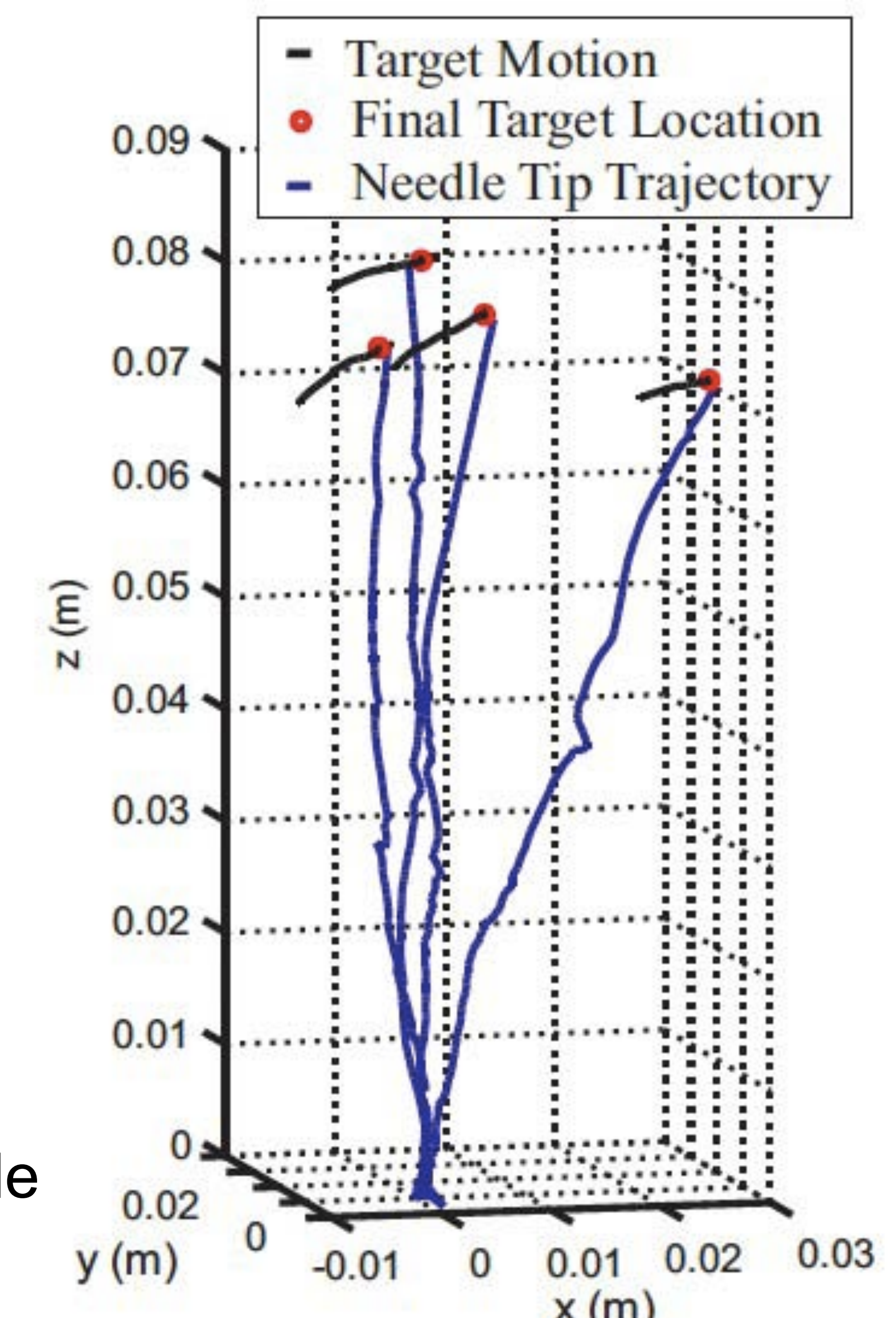
Where along this spectrum should we be?

Control





Trial #	Target Displacement (mm)	Tip Error (mm)
1	9.1	1.4
2	6.5	0.7
3	11.3	1.3
4	10.3	0.9

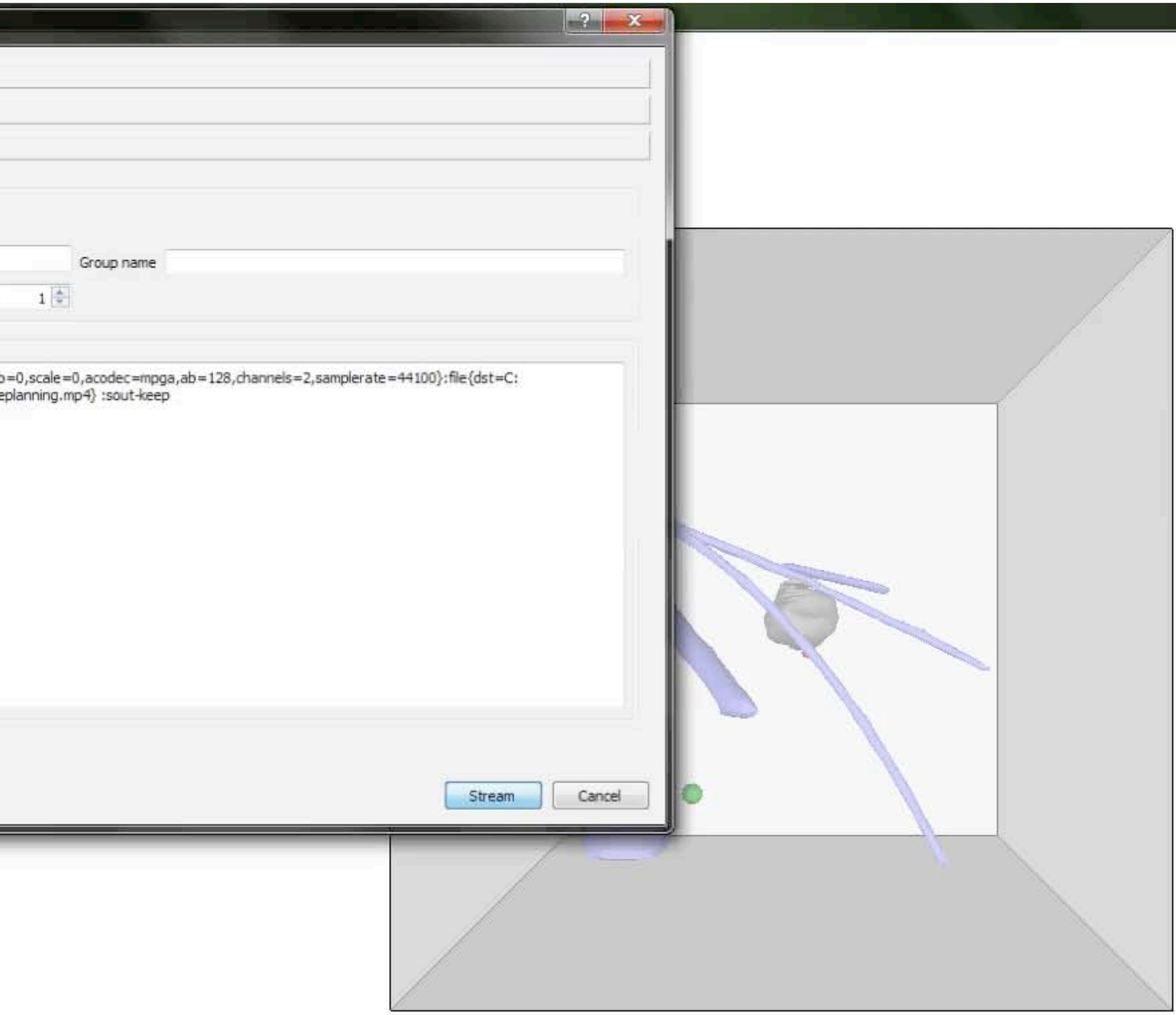


Trial #	Target Point (mm)	Tip Error (mm)
1	[−20 −20 85]	0.4
2	[0 −20 85]	0.2
3	[20 −20 85]	0.4
4	[−20 0 85]	0.5
5	[0 0 85]	1.3
6	[20 0 85]	0.3
7	[−20 20 85]	0.4
8	[0 20 85]	0.3
9	[20 20 85]	0.3

Trial #	Target Point (mm)	Tip Error (mm)
1	[0 0 100]	0.4
2	[7.5 7.5 100]	0.5
3	[−7.5 −7.5 100]	0.1
4	[−7.5 7.5 100]	0.8
5	[7.5 −7.5 100]	0.2

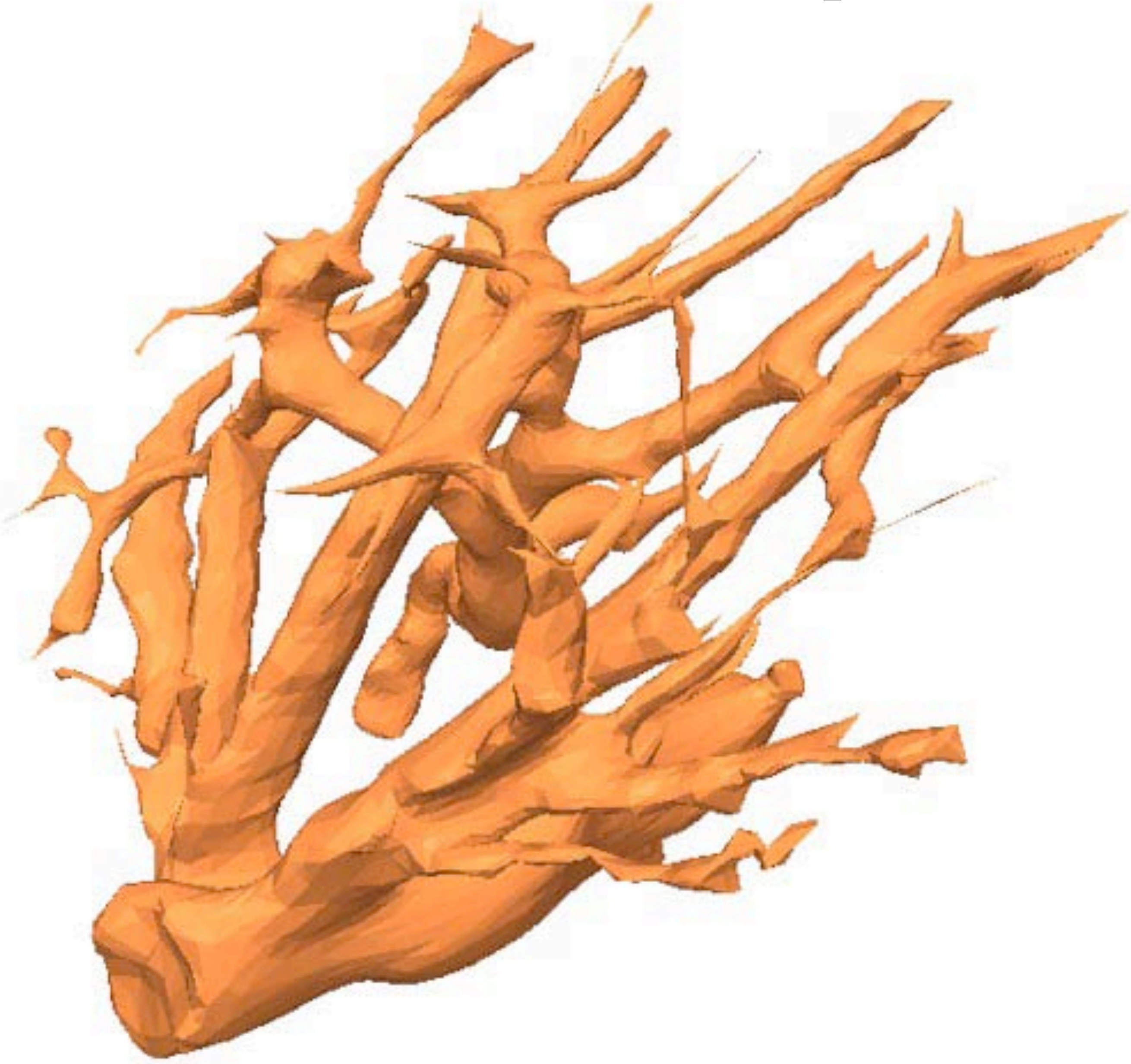
Rucker, Das, Gilbert, Swaney, Miga, Sarkar, and Webster, “Sliding Mode Control of Steerable Needles. TRO, (In Press).

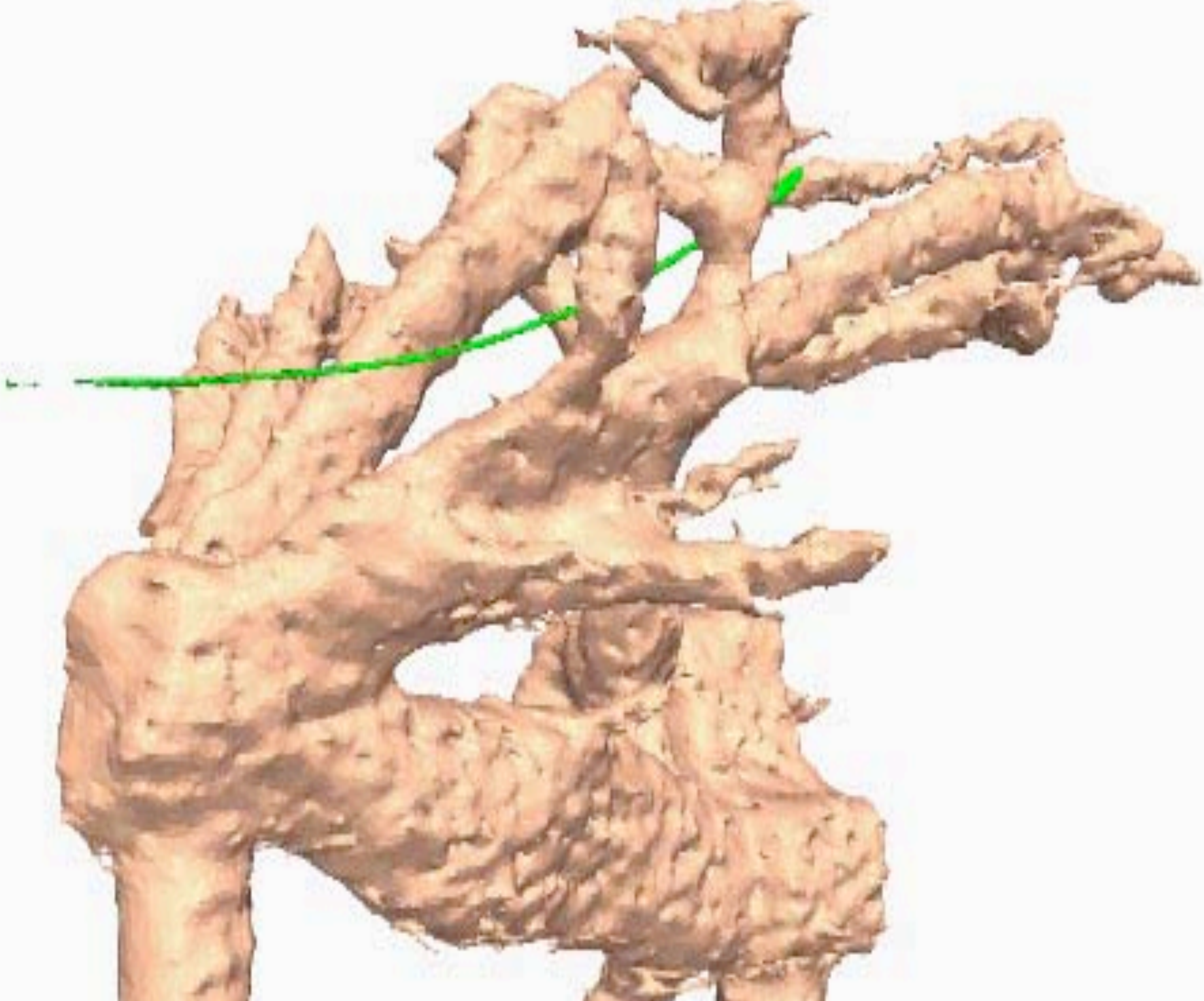
Rapid Replanning as Control

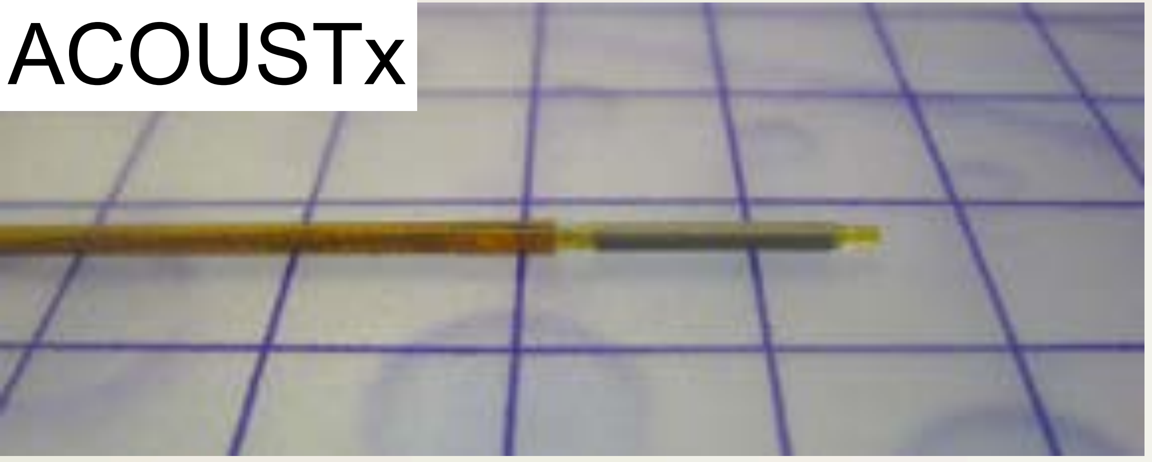


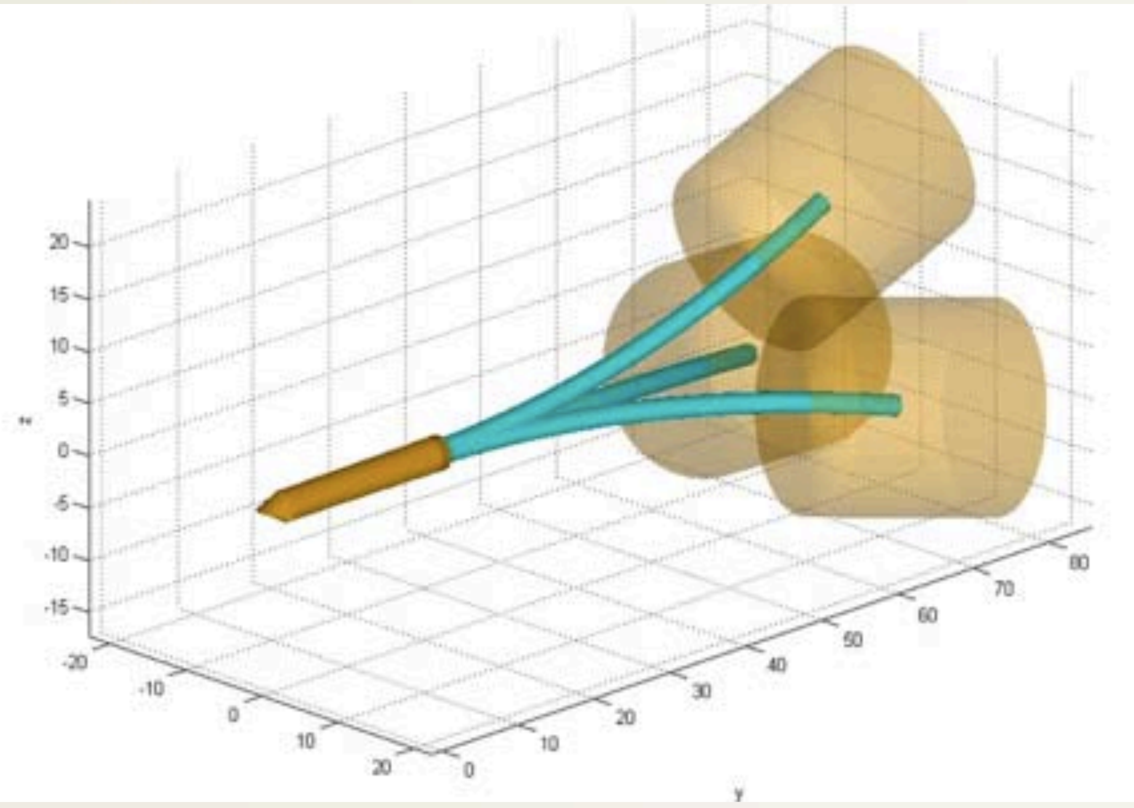
C P

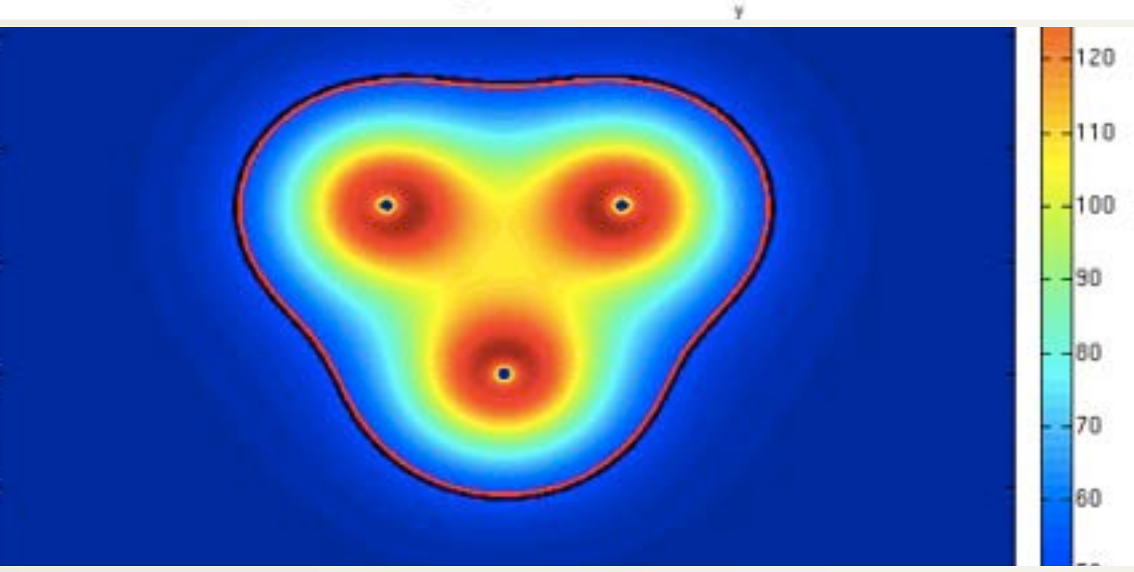
Experimental Setup

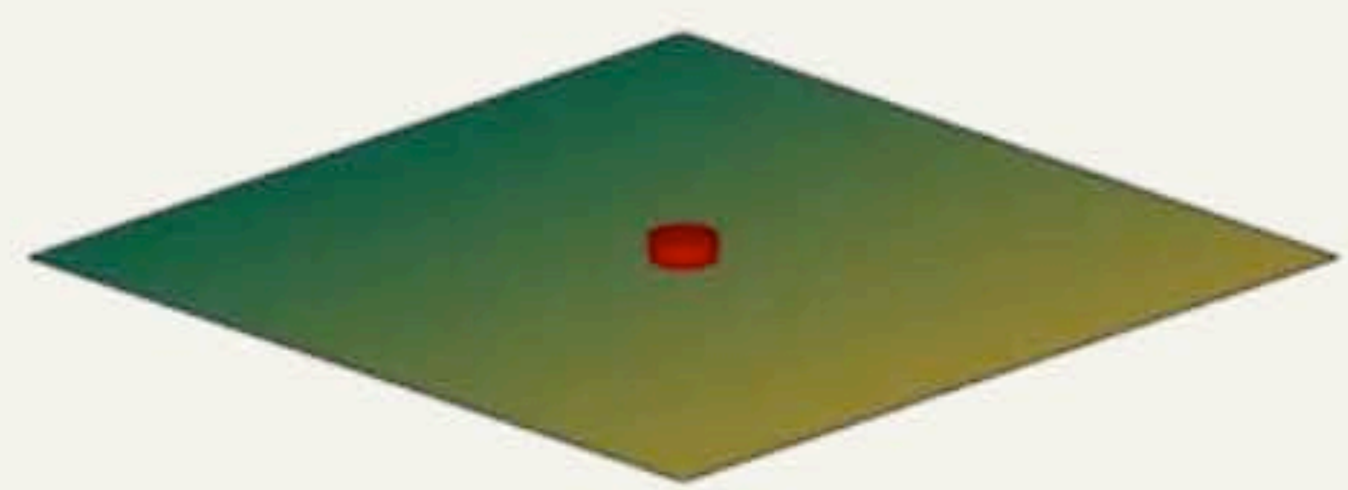




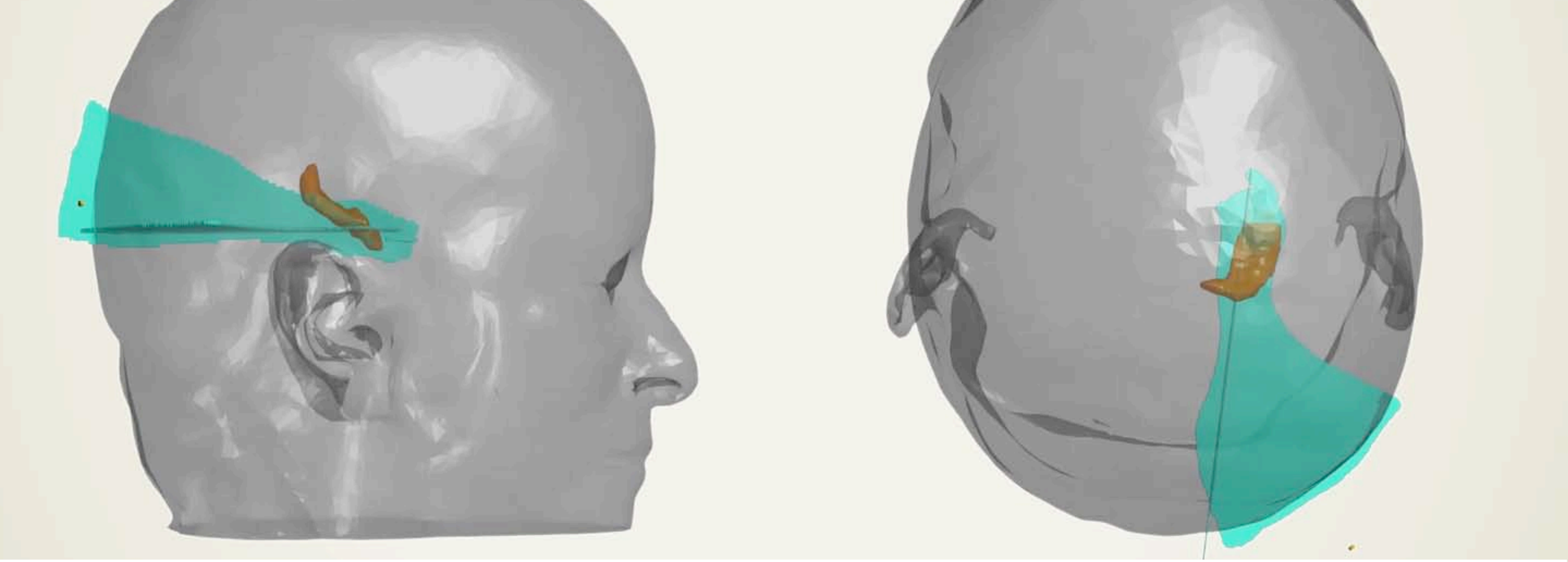


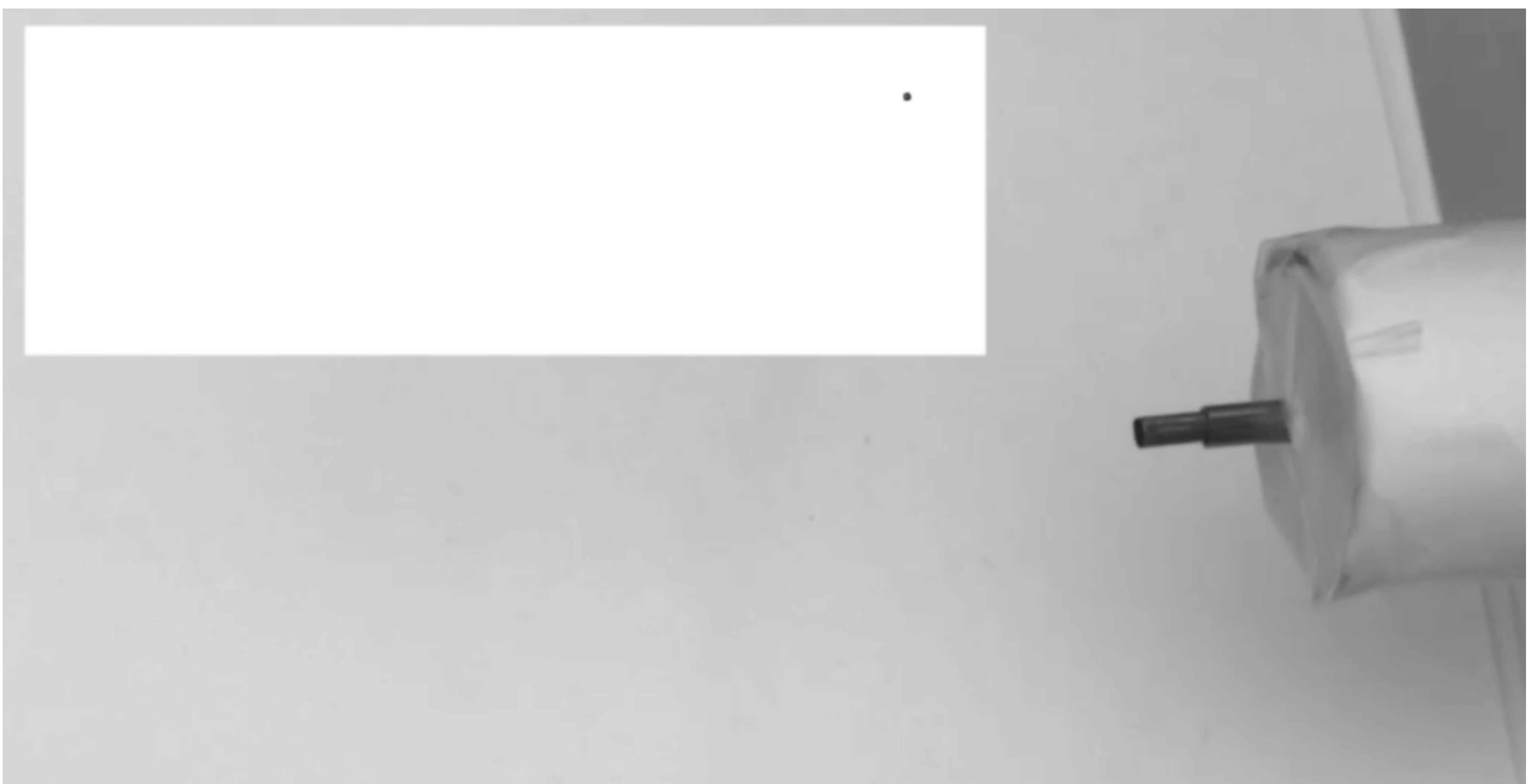






Gilbert and Webster, "Can Concentric Tube Robots Follow the Leader?" ICRA 2013.





Acknowledgements

Skull Base Surgery:

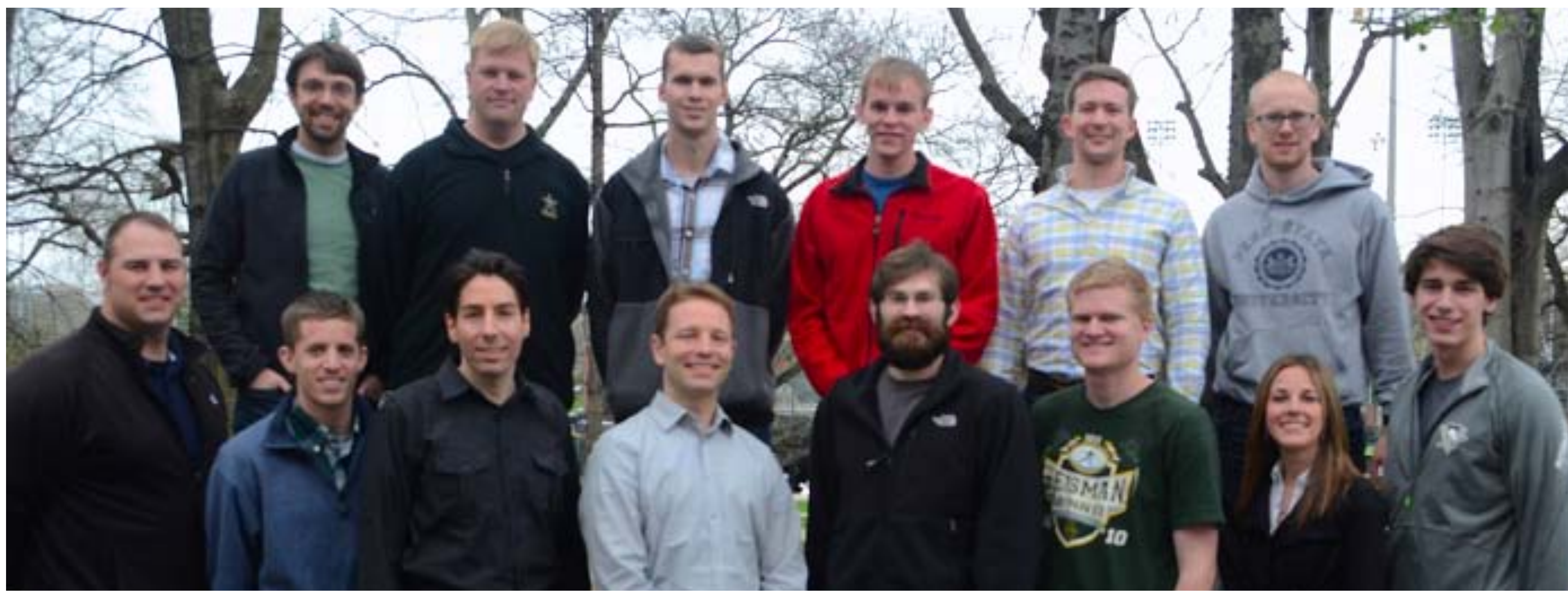
Rucker, Burgner, Gilbert, Swaney, Croom, Nill, Bruns, Hendrick, Bekeny, Weaver, Russell - VU

Concentric Tube Robots (Modeling/General):

Okamura - Stanford   Cowan, Chirikjian, Taylor - Johns Hopkins   Jones - Miss. St.
Lyons, Alterovitz - UNC   Romano - Penn   Rucker, Lathrop, Gilbert, Swaney, Burgner - VU

Bevel Tip Needle Steering:

Okamura, Chirikjian, Cowan, Kim, Kallem, Goldberg, Alterovitz, Romano, Burgner, Rucker, Swaney, Patil, Das, Sarkar



Funding:

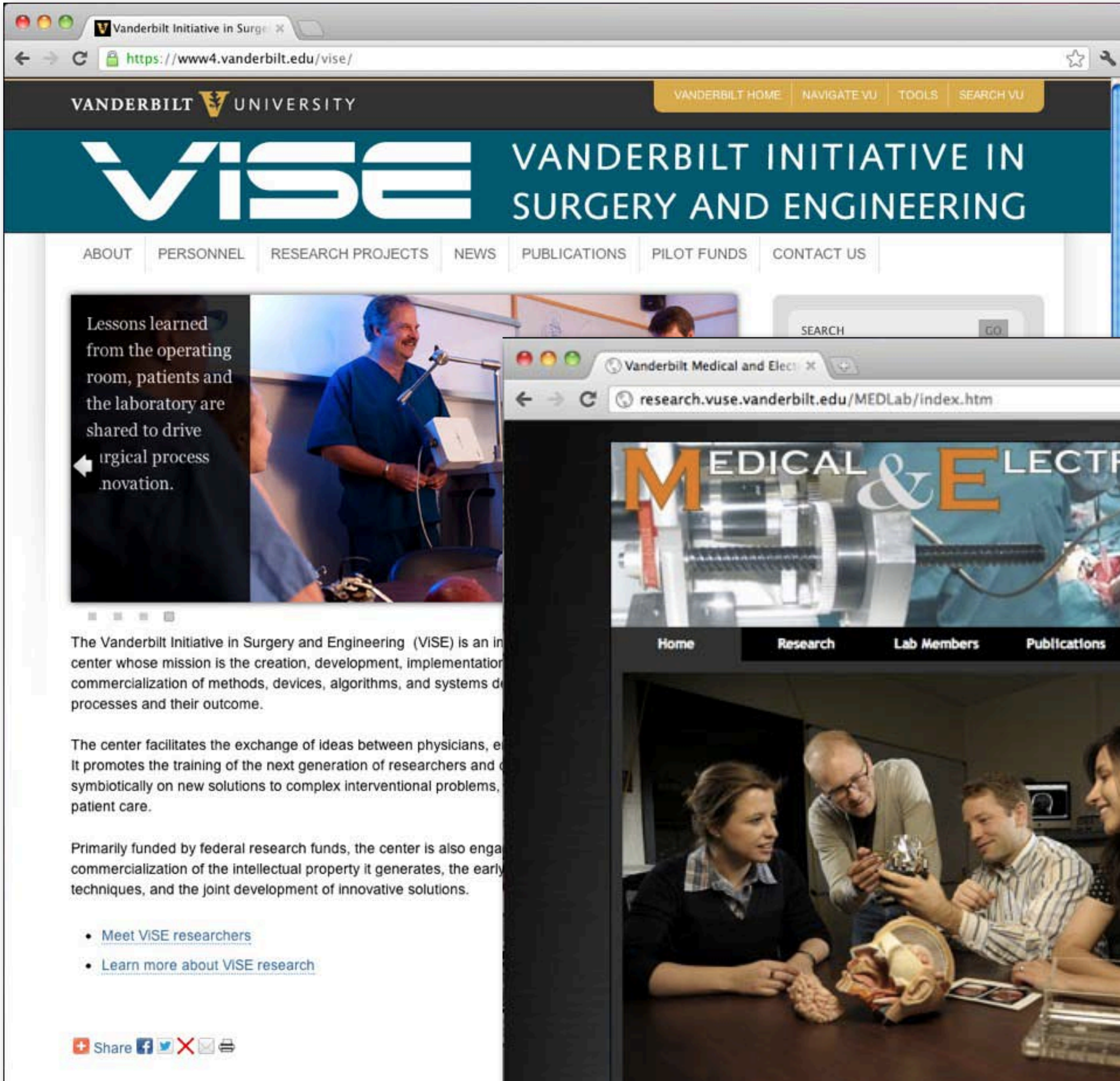
NIH:
- NCI: R44
- NIBIB: R21, R01

NSF:
- CAREER
- CBET
- 5 Fellowships

Others:
- Intuitive Surgical
- Korea Inst. Sci. Tech.
- The Thomas Family

For More



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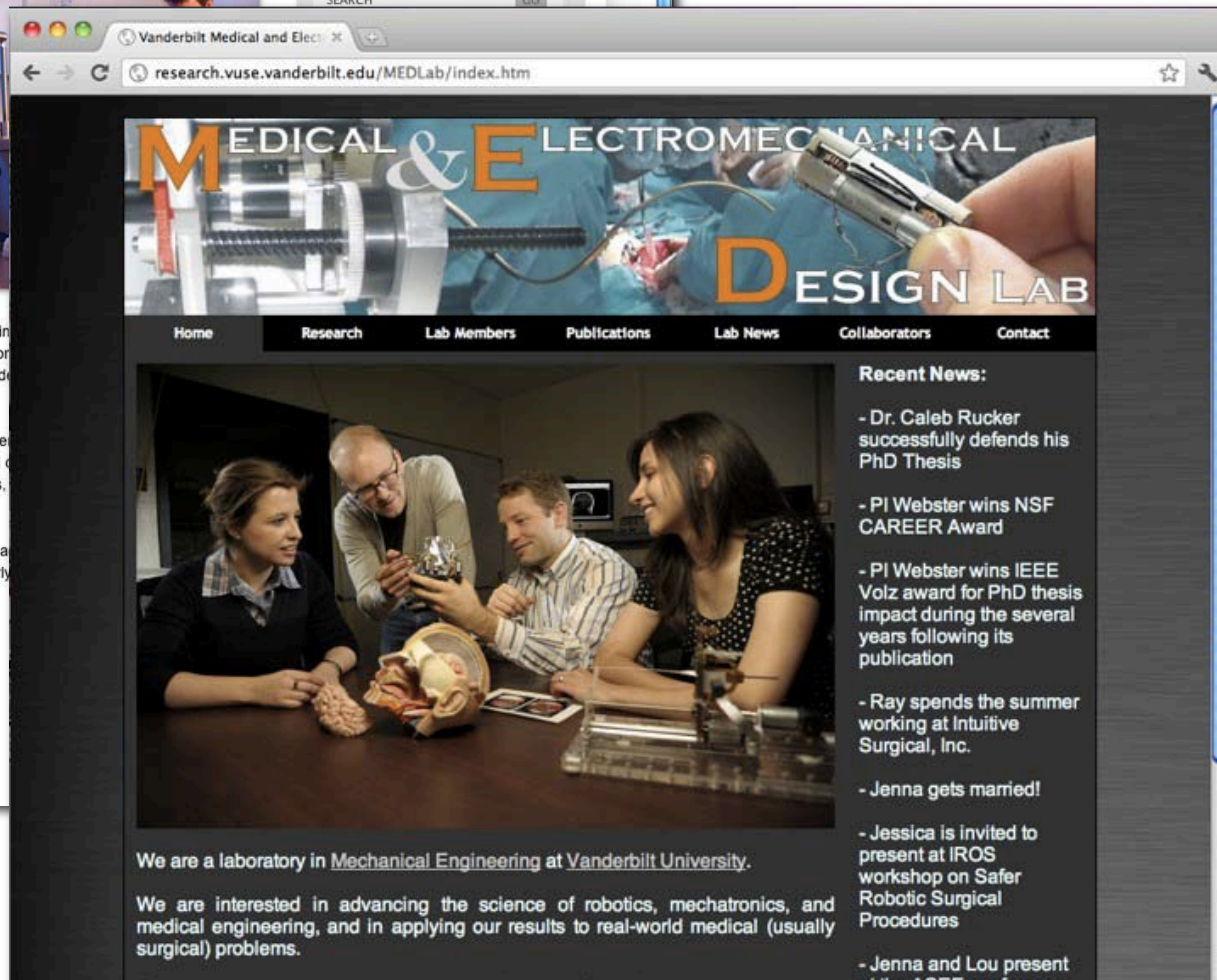

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Questions?