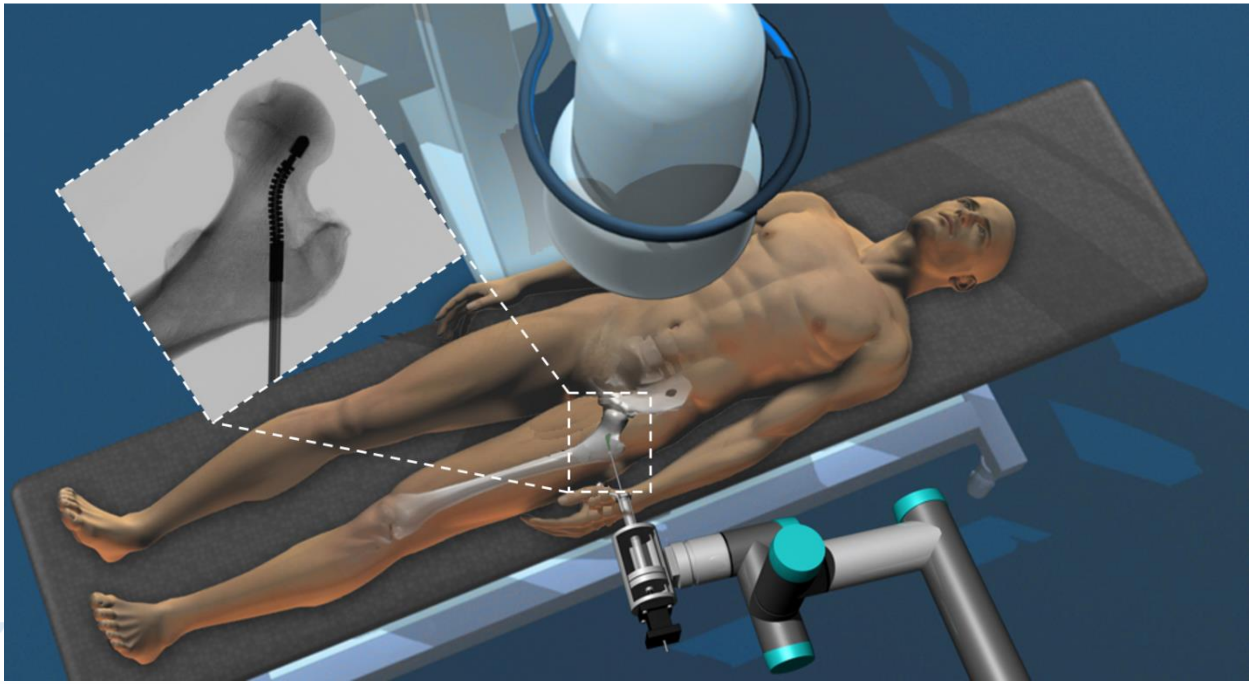
Dexterity and Autonomy in Minimally Invasive Medical Robotics Interventions



Farshid Alambeigi, PhD Candidate

Class of 2019 Siebel Scholar

Laboratory for Computational Sensing and Robotics (LCSR)

falambe1@jhu.edu

NIH Research supported by NIH/NIBIB grant R01EB016703.

Nov. 27th, 2018

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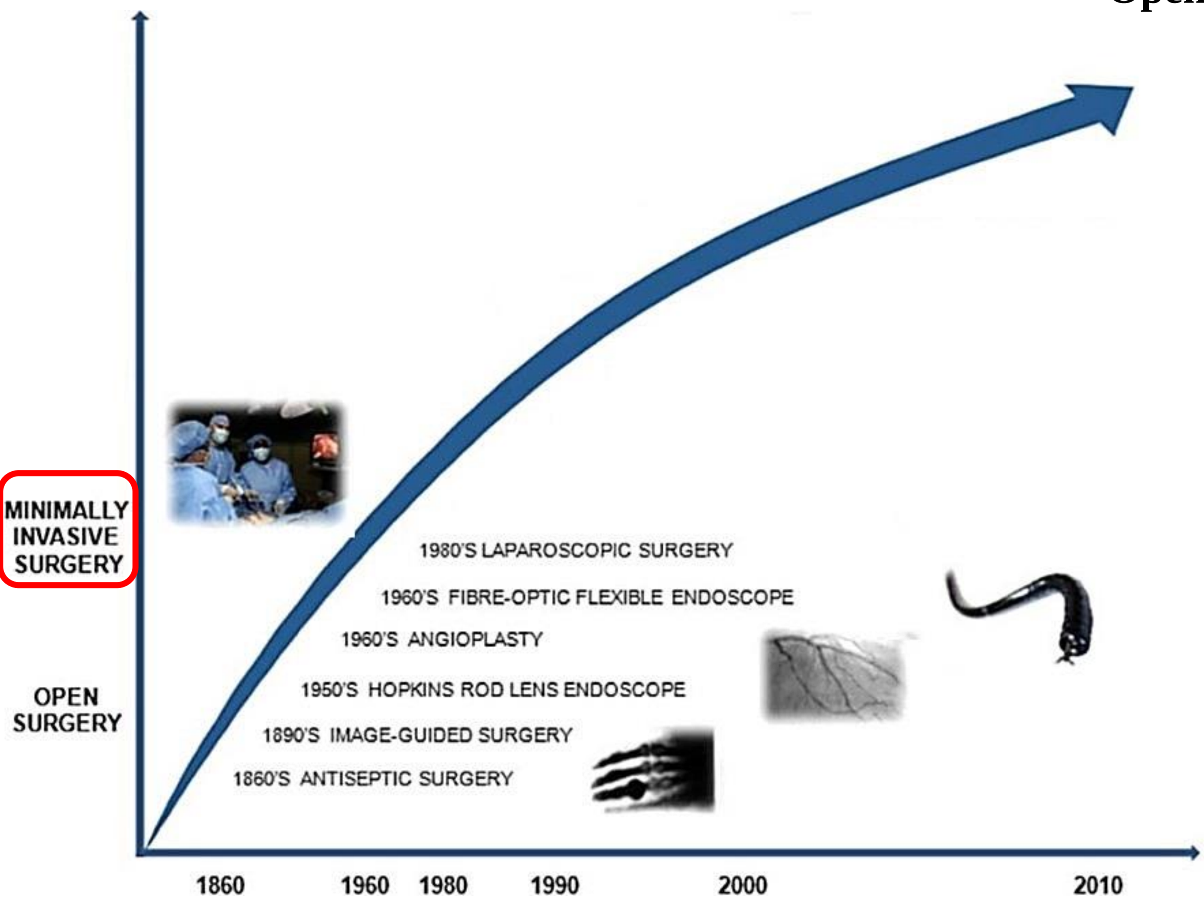
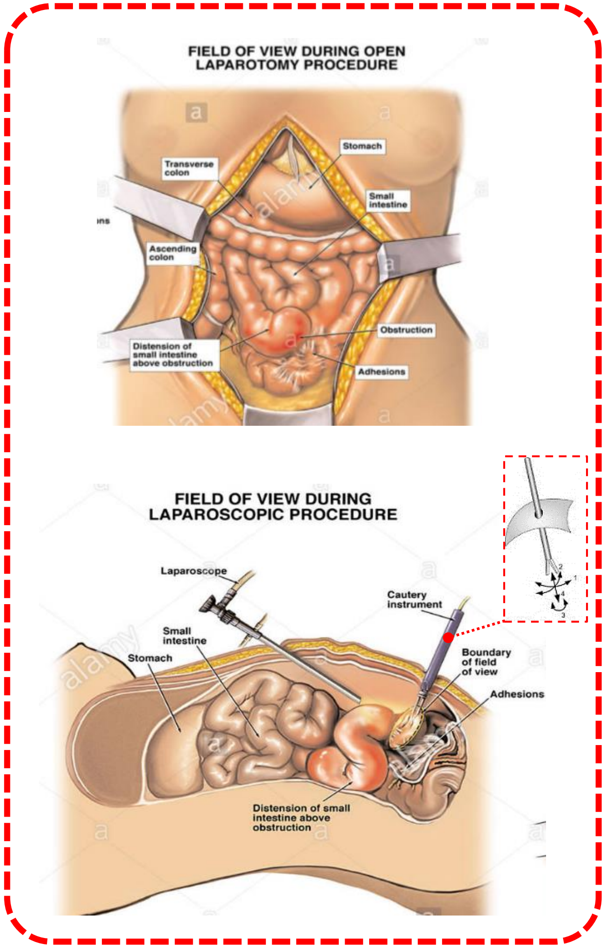
Key Milestones in Surgical Technology

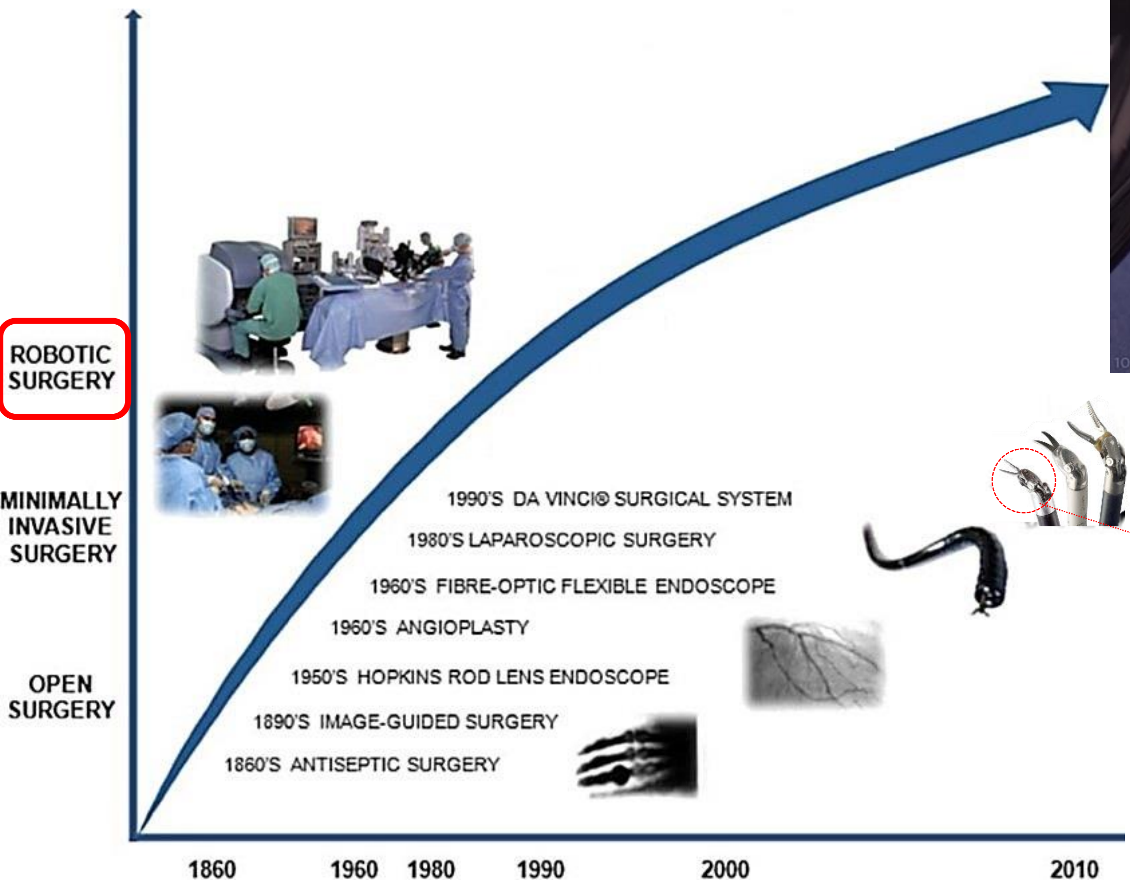


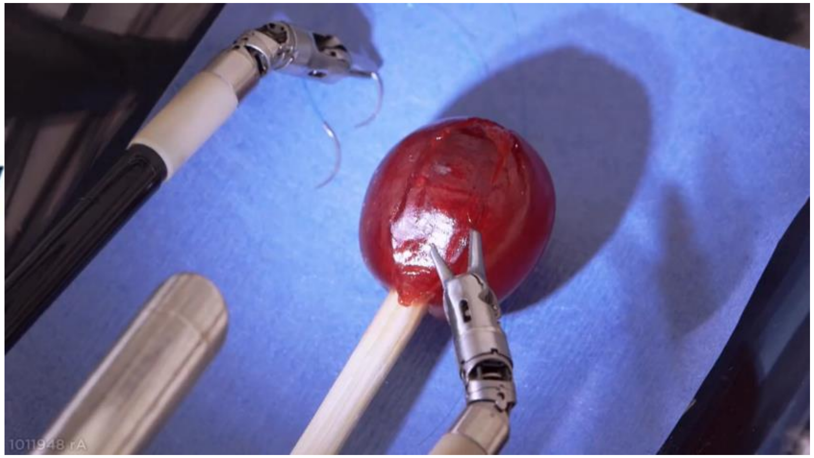
Open vs. Minimally Invasive Surgery (MIS)



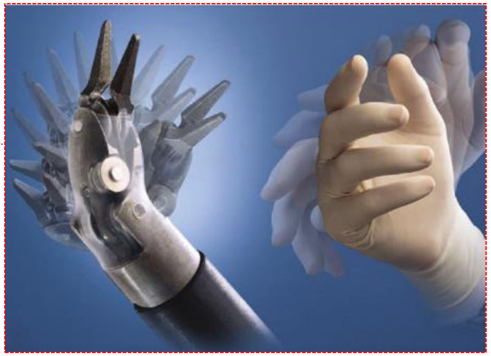
Vitiello et al., "*Emerging Robotic Platforms for Minimally Invasive Surgery*", IEEE REVIEWS IN BIOMEDICAL ENGINEERING, 2012.

Key Milestones in Surgical Technology





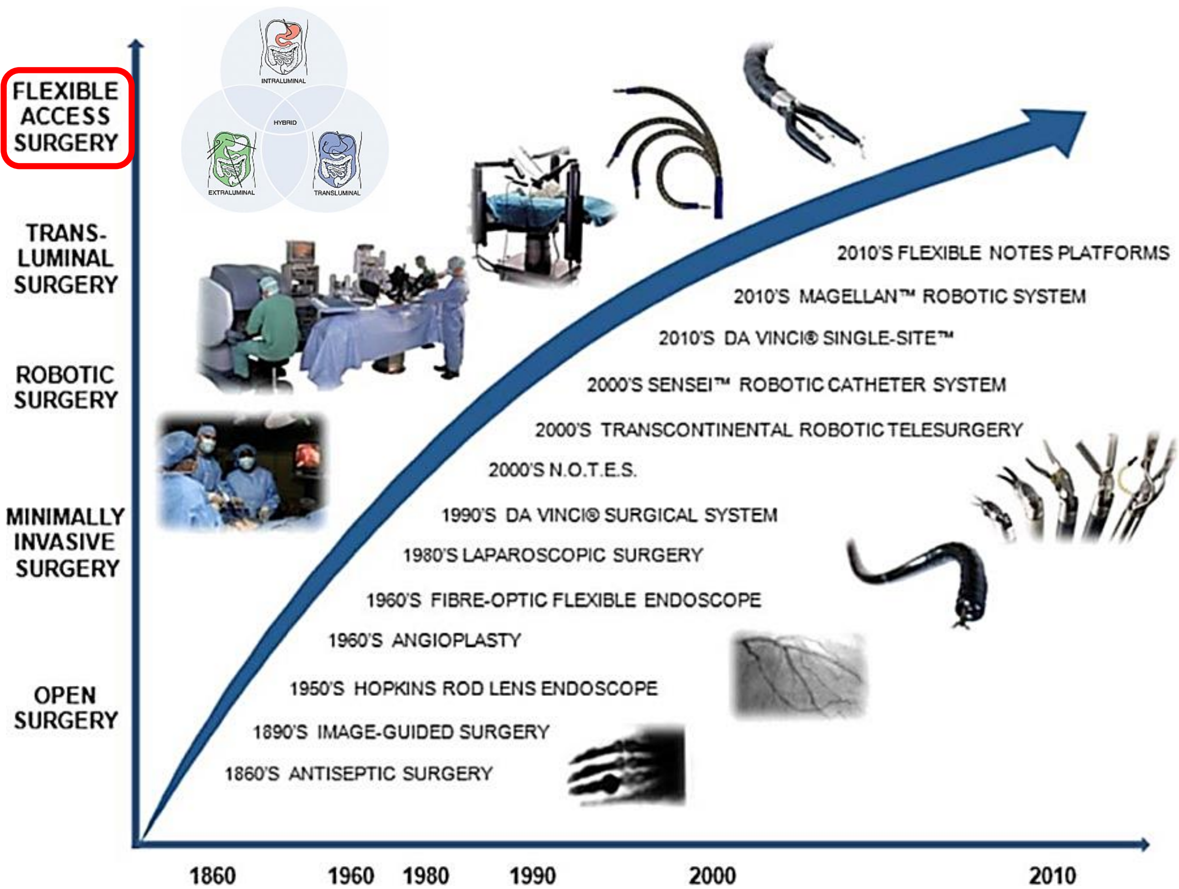
Credit: Intuitive Surgical Inc.



Vitiello et al., "*Emerging Robotic Platforms for Minimally Invasive Surgery*", IEEE REVIEWS IN BIOMEDICAL ENGINEERING, 2012.

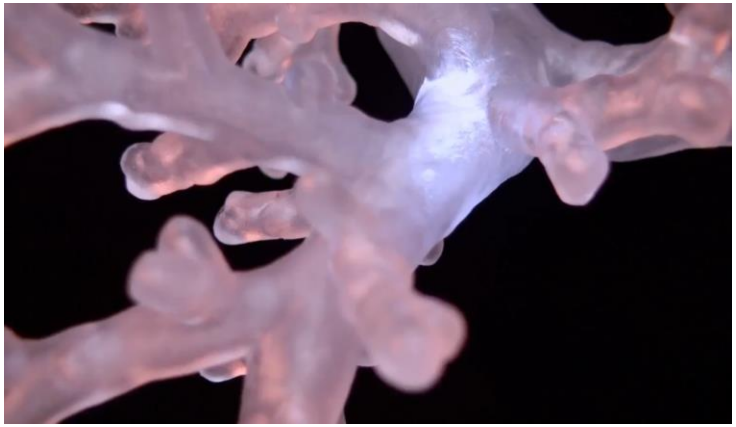
Key Milestones in Surgical Technology

Flexible Access Surgery: The ability to adequately **access** different target anatomy via an MIS Procedure.



Vitiello et al., "*Emerging Robotic Platforms for Minimally Invasive Surgery*", IEEE REVIEWS IN BIOMEDICAL ENGINEERING, 2012.

Intuitive Surgical da Vinci Sp



Auris Health Inc., Monarch Platform

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Continuum Manipulators (CMs) vs. Conventional Robots

No. DoF > Required DoF: **Redundant** Robot

No. DoF >>> Required DoF: **Hyper Redundant** Robot

No. DoF ⟶ ∞: **Continuum Robot**

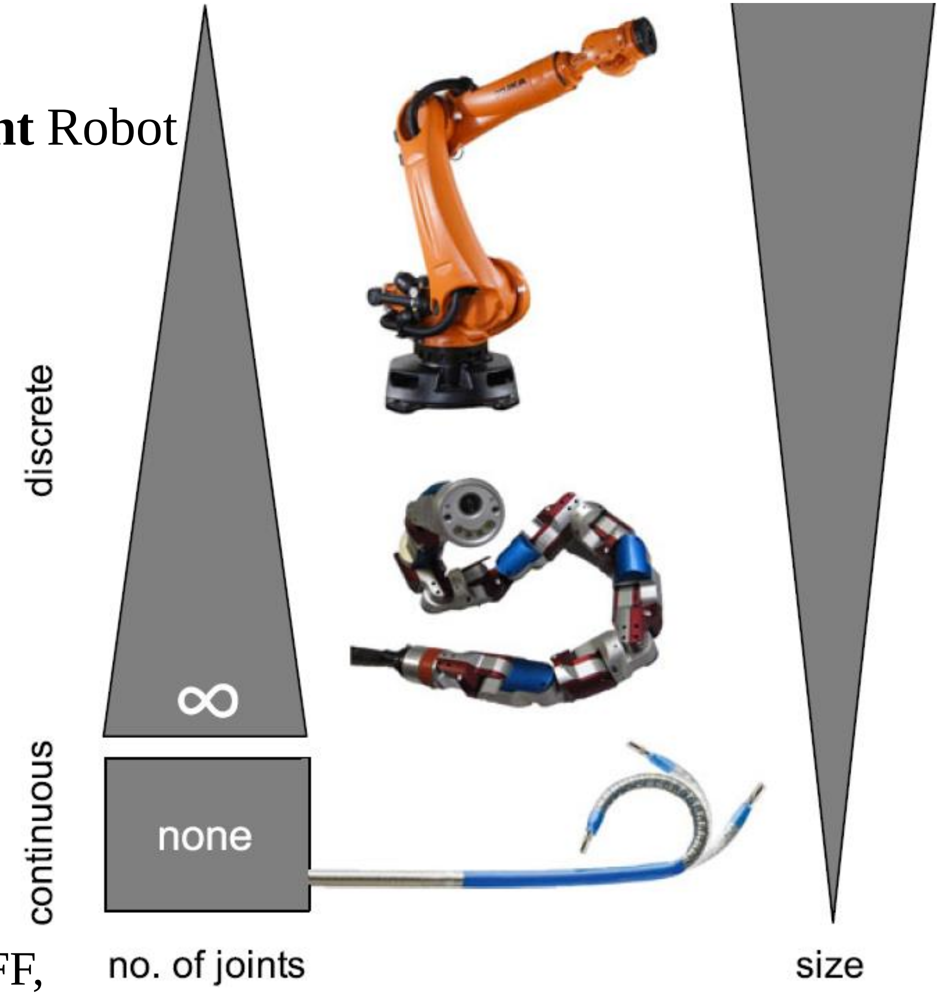
➢ CMs do NOT contain rigid links and joints

Advantages:

- ✓ More dexterity and Accessibility,
- ✓ Added Safety;
- ✓ Potential Miniaturization

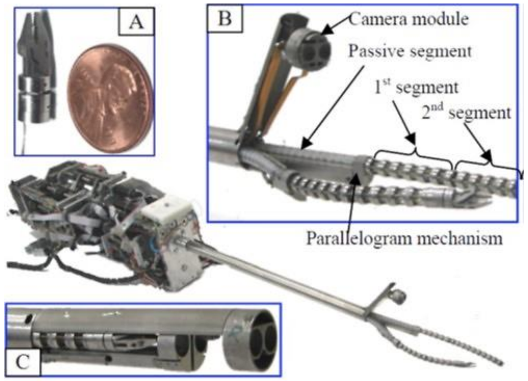
Challenges:

- ✓ Design and Fabrication,
- ✓ Shape Sensing,
- ✓ Modelling and Control,
- ✓ Stiffness and Structural Stability Trade-OFF,
- ✓ Low Payload/External Load Capacity

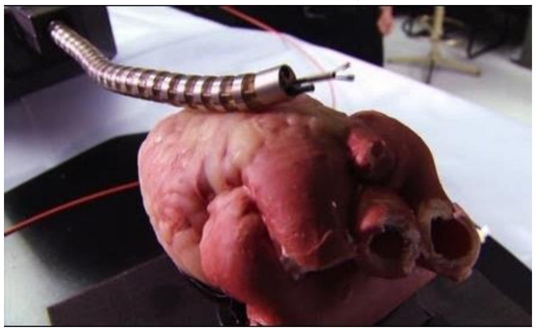


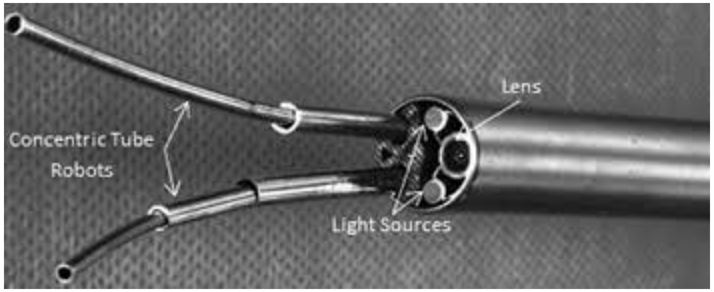
J. Burgner-Kahrs, et al. "*Continuum Robots for Medical Applications:A Survey*" ***Transaction On Robotics,*** **2015**

Flexible Access Surgery for Soft Tissues???

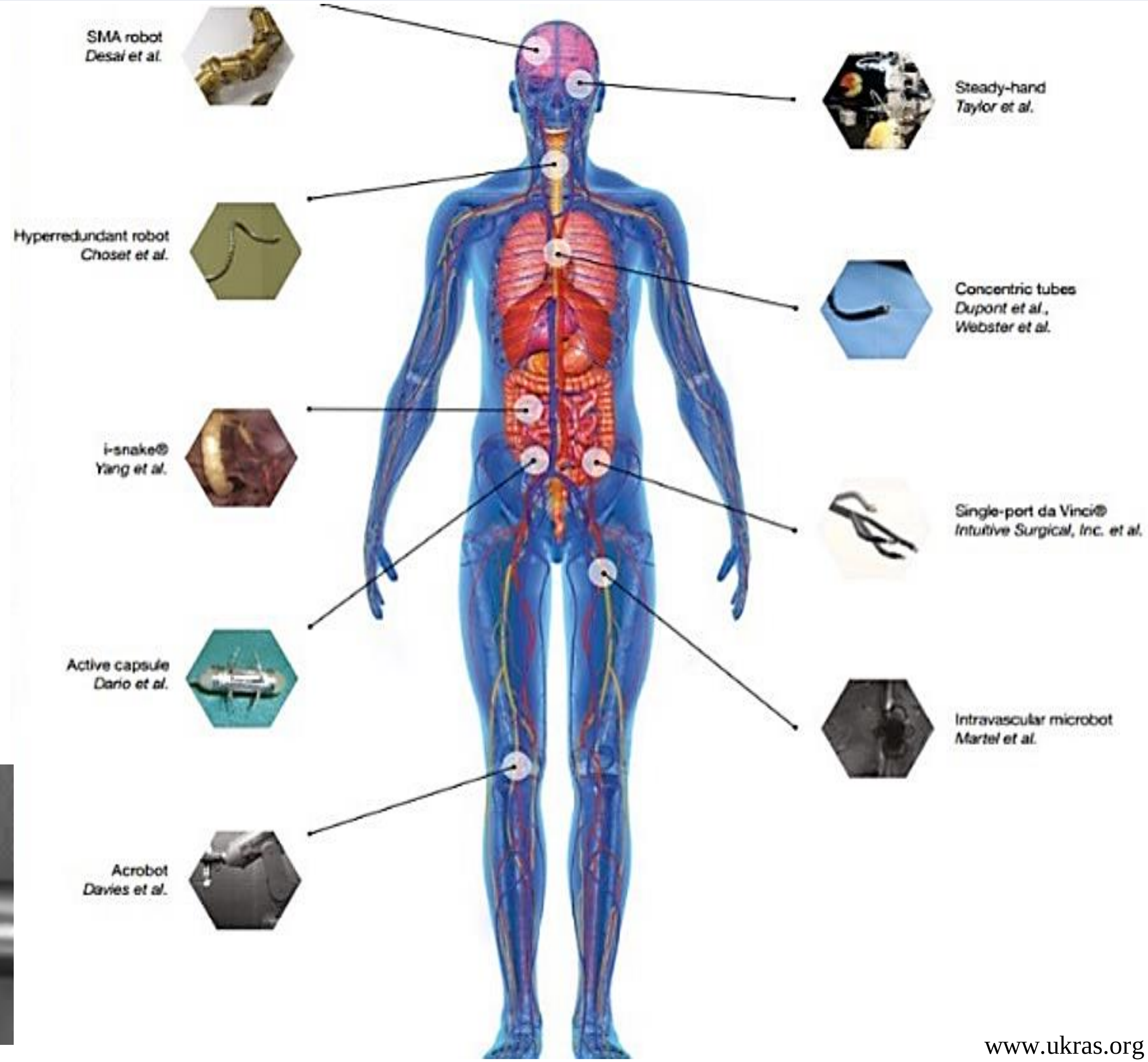


Dr. Simaan, Vanderbilt university


Dr. Choset, Carnegie Mellon University



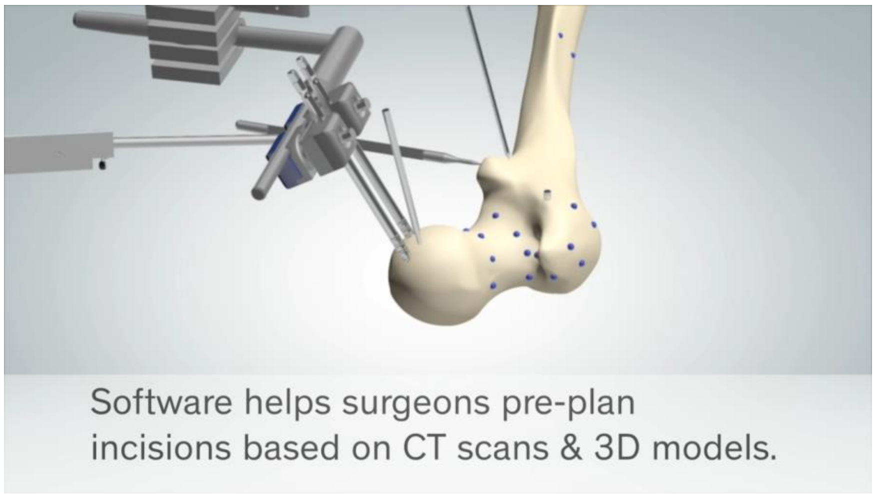
Dr. Webster, Vanderbilt university



www.ukras.org

Flexible Access Surgery for Hard Tissues

- Need for dexterity in Orthopedic Surgery (*interacting with hard bone*)
- Most of the tools are Rigid and even robots are using rigid tools!
- The **Challenge** is using a Deformable Instrument on Hard Tissues!

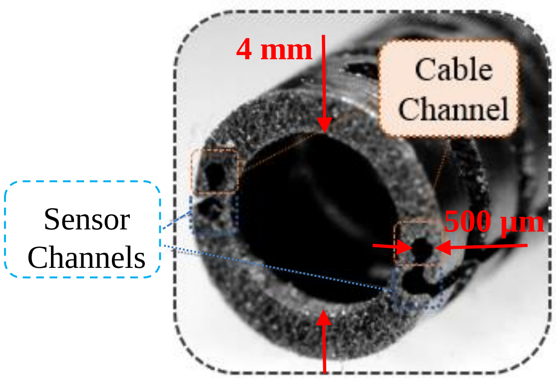


The TSolution One, THINK Surgical Inc.

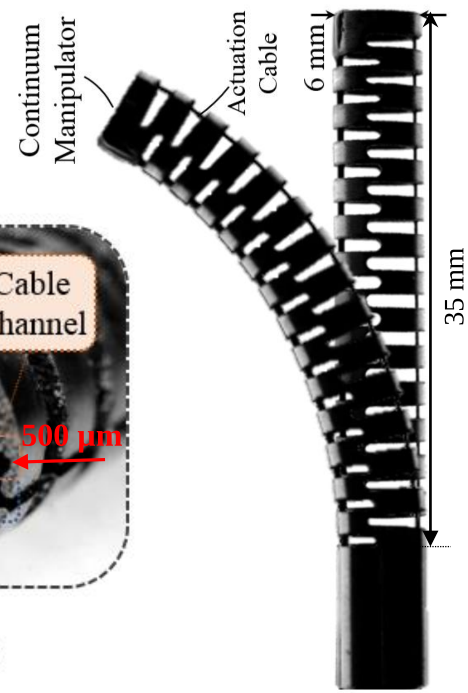
Blue Belt Technologies, Inc.

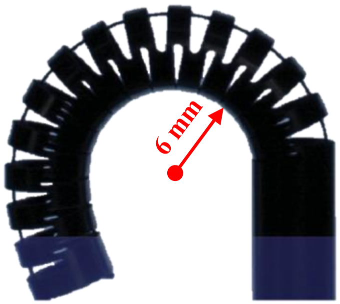
Ortho-Snake: A Continuum Dexterous Manipulator (CDM)

- Ortho-Snake is made of nitinol tubes with outer diameter of 6 mm and a 4 mm tool Channel for inserting different tools.
- Planar bending to large curvatures up to 166.7 m^{-1} .
- High Bending Capability and Structural Stiffness .
- C- and S-shape capability.

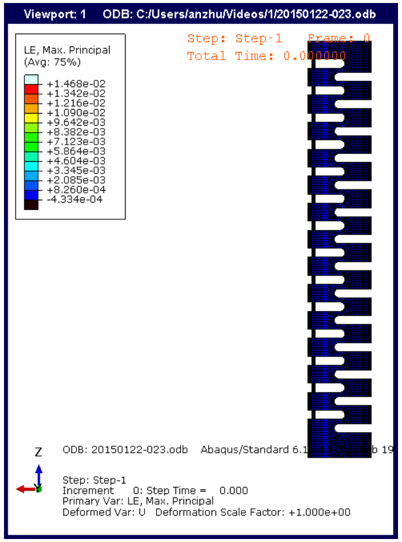


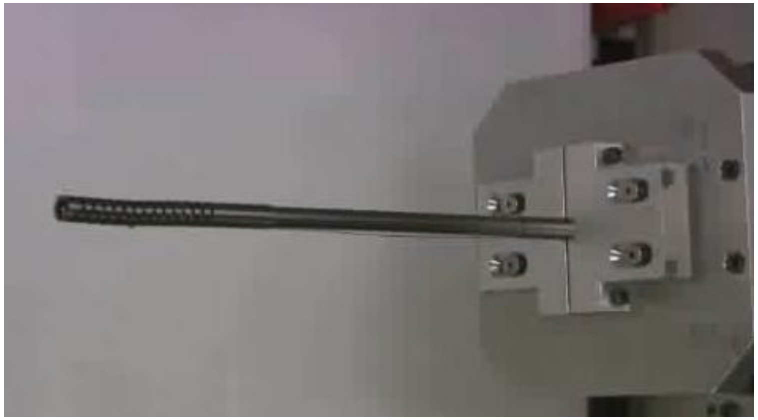
CDM Tip





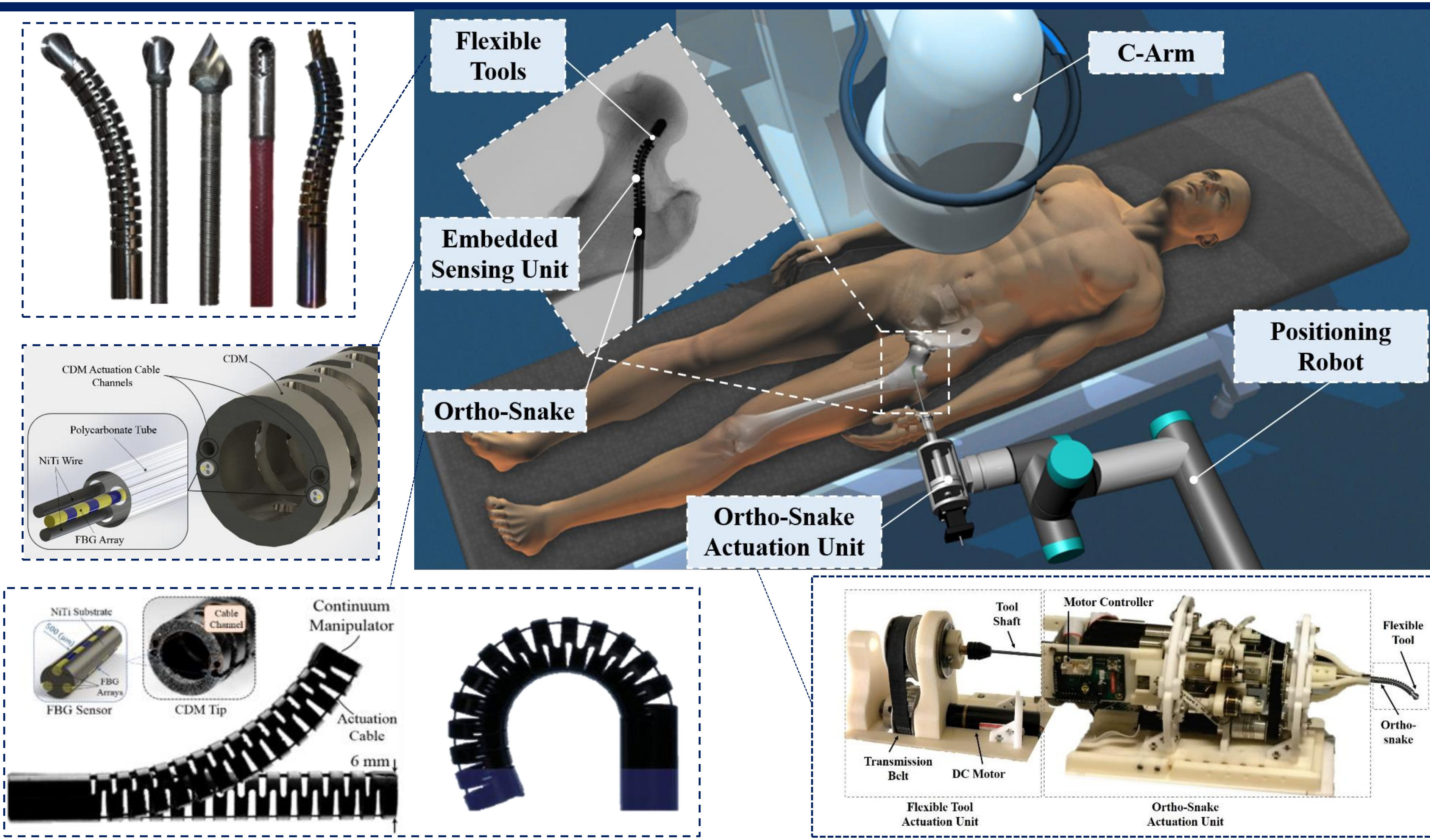
Highly Deformable Structure





S-Bend Capability

A Robotic System for Minimally-Invasive Orthopedic Surgeries



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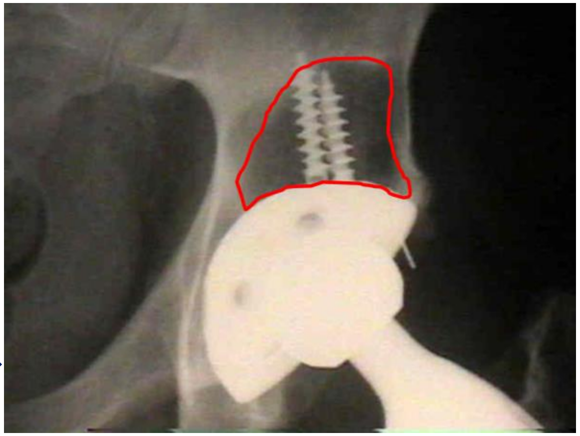
Less-Invasive Treatment of Osteolytic Lesions

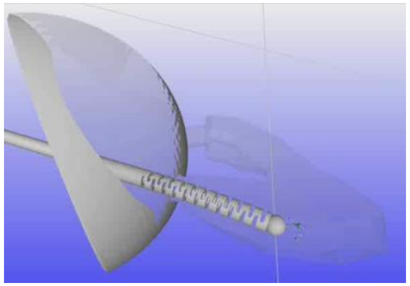
- **Indication**
  - ✓ Osteolysis (Bone Degradation)) behind a well-fixed acetabular component
  - ✓ Leads to component loosening and failure of THA
- **Surgical Goals**
  - ✓ Less invasive removal of the osteolytic lesion
  - ✓ Treatment of the osteolysis without full replacement of the acetabular component
- **Surgical Procedure**
  - ✓ Access the lesion through the screw holes of the acetabular component (minimally invasive)
  - ✓ Remove and grafting the lesion
  - ✓ Replace the polyethylene liner
- **Current Limitation**
  - ✓ Poor accessibility due to **rigidity** of Instruments
  - ✓ Less than 50% of the lesion is actually cleaned and grafted

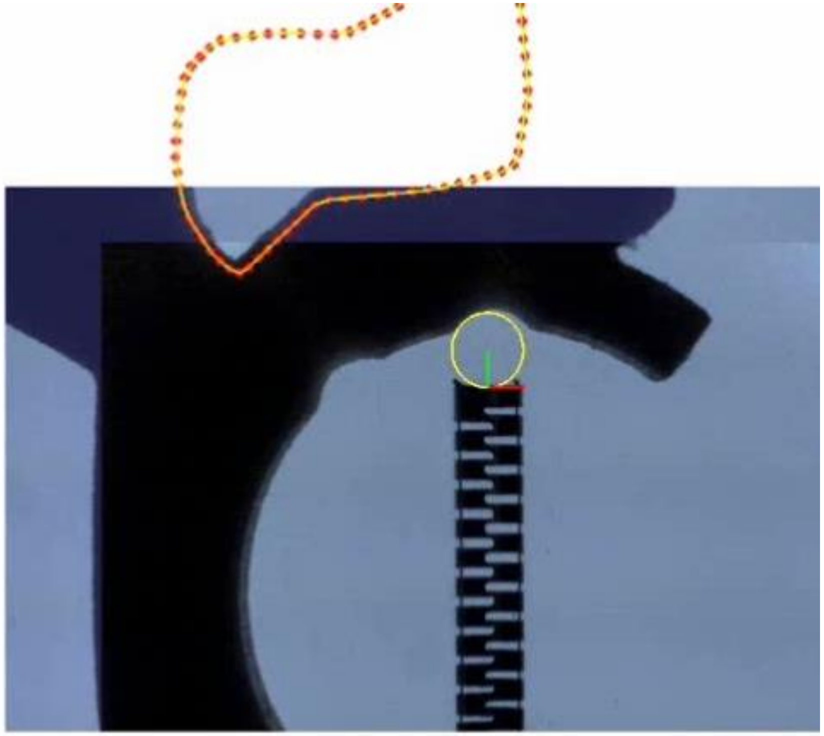


Osteolysis Treatment Using Ortho-Snake (Accessibility Test)

➢ Simulation of Ortho-Snake's Workspace inside a simulated Lesion

➢Experiments show this CM is able to explore **over 94%** of the lesion space.



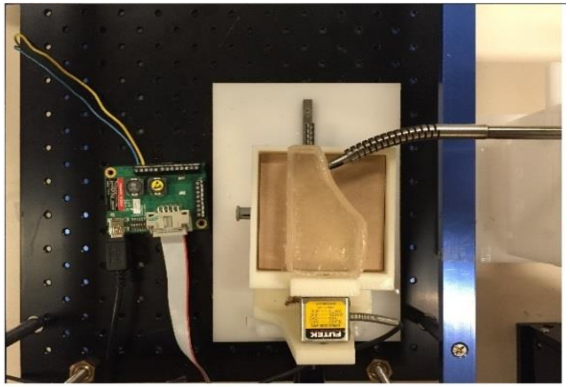


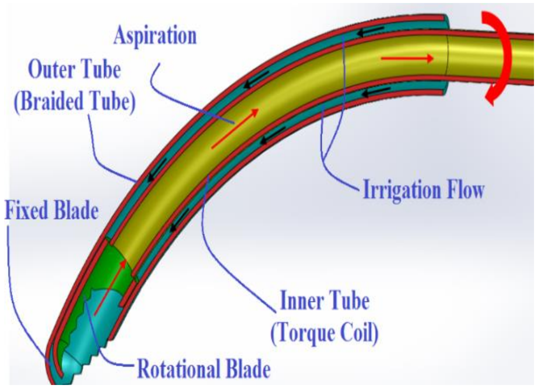
R. J. Murphy et al, Robotica, 2014

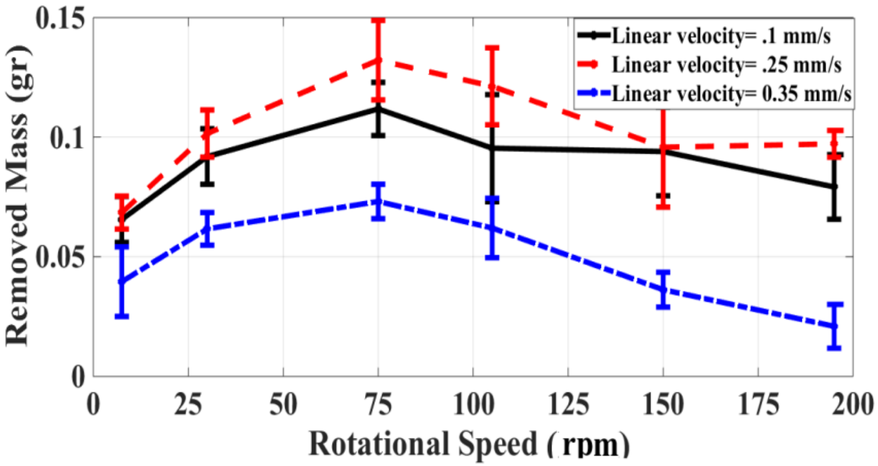
Simulated Lesion Geometry

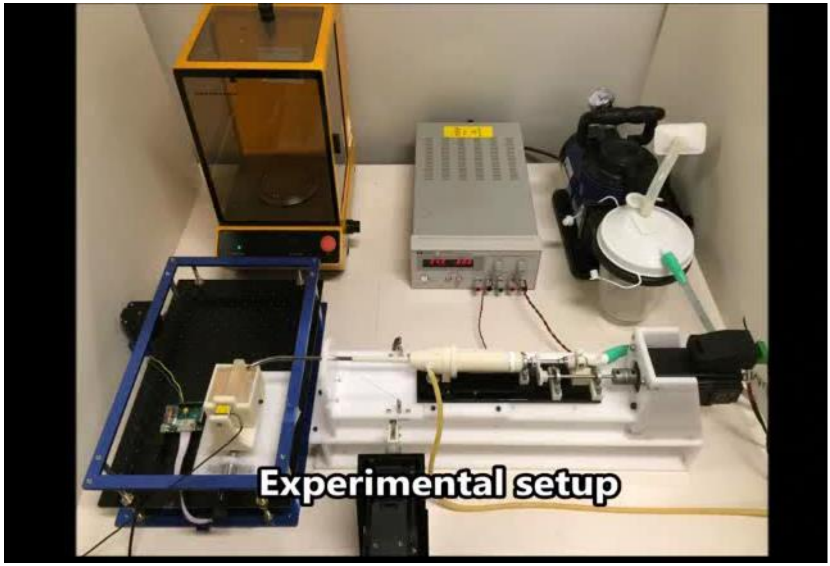
Ortho-Snake Passing through an Implant

A Debriding Tool for Removing Soft Lesions (Stability Test)





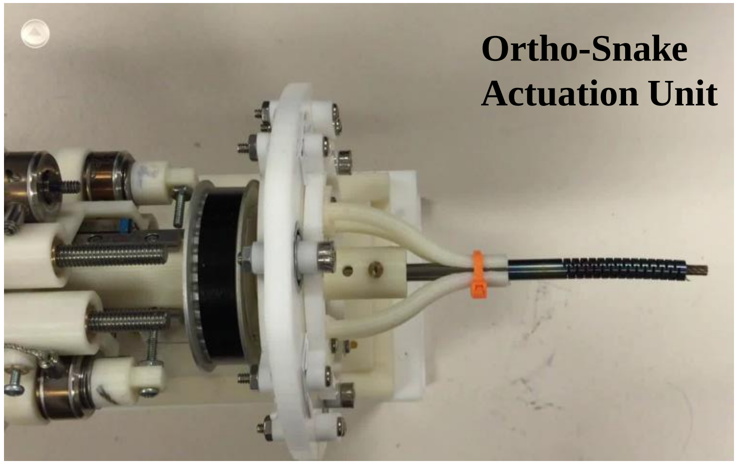


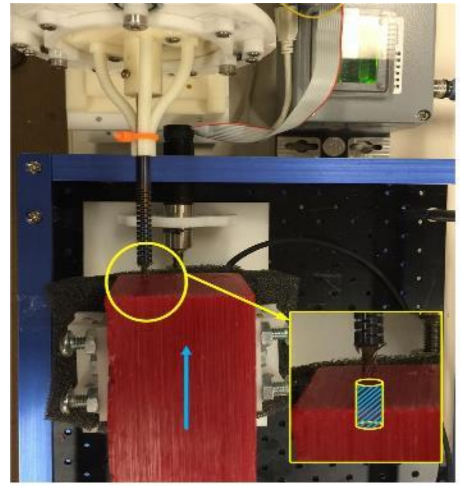


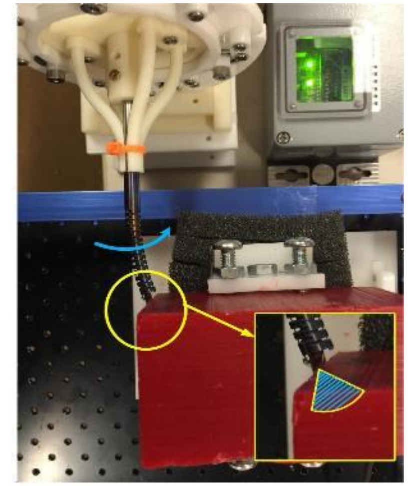
Contact force is minimum in **75 rpm** →Best Performance

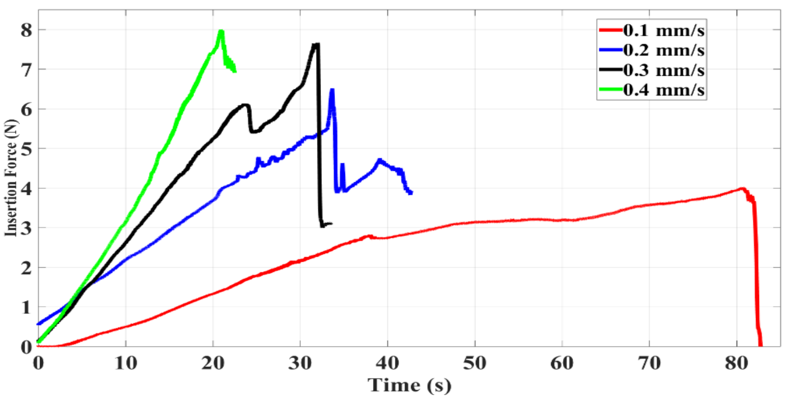
F. Alambeigi, et al. "*Design and Characterization of a Debriding Tool for Treatment of Oseteolysis*" ***ICRA, 2016.***

A Milling Tool for Removing Hard Lesions (Stability Test)

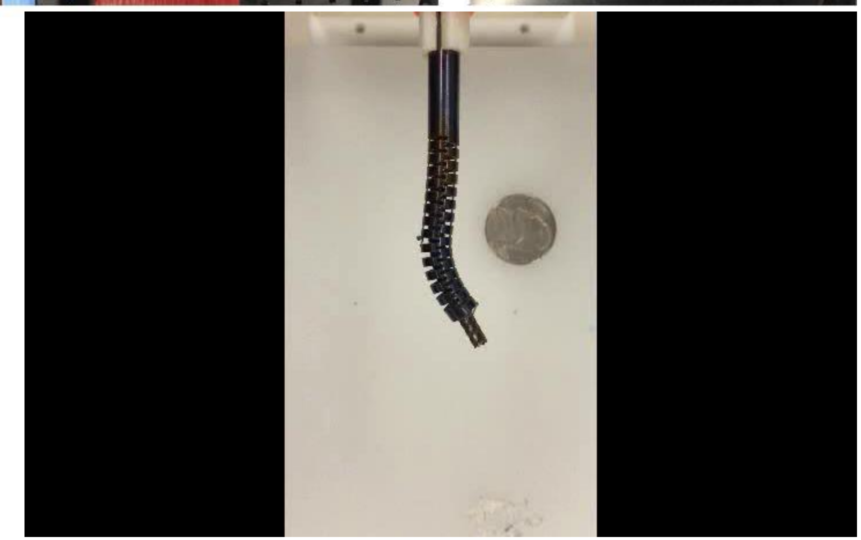






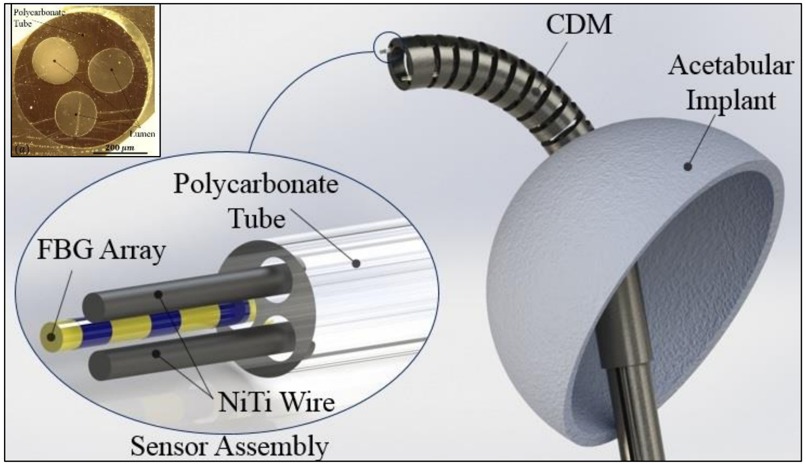


Speed ↑ → Contact Force ↑ → Buckling ↑

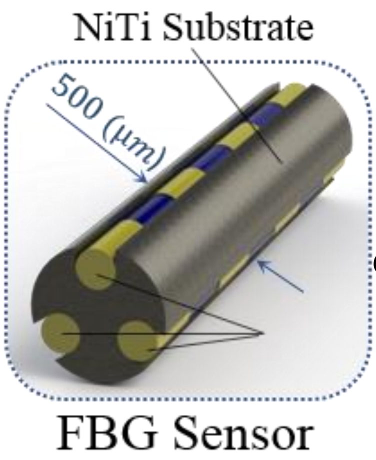


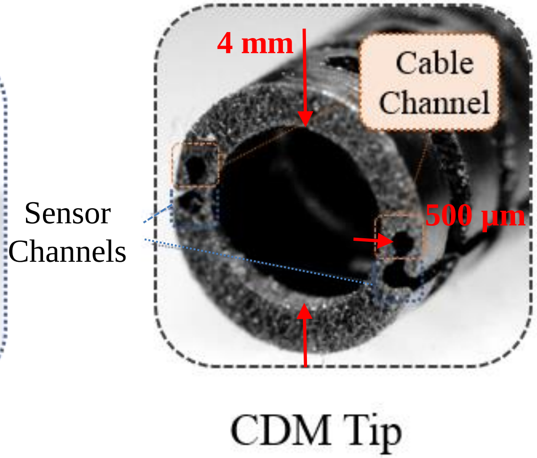
F. Alambeigi, et al. "*Toward Robot-Assisted Hard Osteolytic Lesion Treatment Using a Continuum Manipulator* "***EMBC 2016.***

Shape Sensing Using Optical Fiber Bragg Gratings (FBG)



- **Goal**
  - ✓ Capturing the shape of Ortho-Snake during various large-deflection bending condition
- **FBG Sensor Integration with CDM**
  - ✓ Sensor passed through channel
  - ✓ Attached to CDM only at tip
- **Geometry**
  - Channel OD 0.5 mm
  - Sensor OD 0.4 mm
- **Challenges**
  - ✓ Repeatable Fabrication and Assembly
  - ✓ Reliable Shape Recovery algorithm
  - ✓ Sensor and CDM not connected throughout the length
  - ✓ Wiggle room between Sensor and CDM





S. Sefaty, M. Pozin, **F. Alambeigi**, et al., IEEE Sensor *2017*. ***(Finalist of the Best Paper Award);*** S. Sefaty, **F. Alambeigi**, et al., ISMR2018

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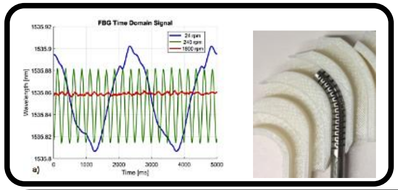
Shape Sensing Using Optical Fiber Bragg Gratings (FBG)

- FBG Wavelength From Interrogator
- Signal Denoising (Optional)
- Find Curvature At FBG Nodes
- Interpolate Curvature For Entire Sensor
- Find Slopes And Position Along Sensor



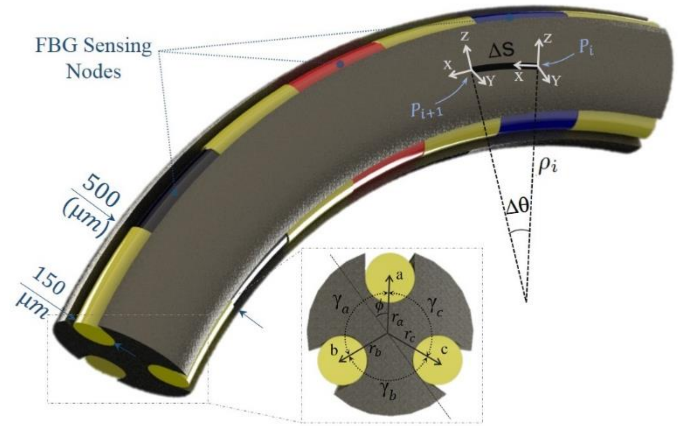
$$\left.\begin{aligned}\frac{\Delta\lambda}{\lambda_B} &= k_\epsilon \epsilon + k_T \Delta T \\ \epsilon &= \delta\kappa\end{aligned}\right\} \Rightarrow \kappa = f(\Delta\lambda)$$

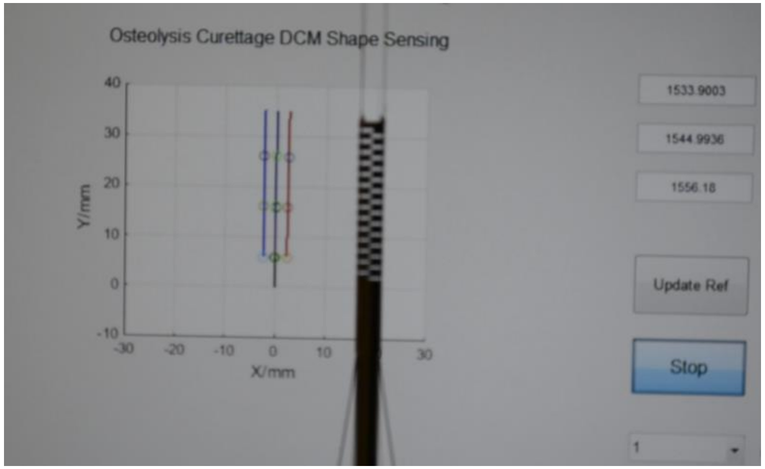
$$\kappa = as + b$$

$$\Delta\theta_i = \kappa_i \Delta s = \frac{\Delta s}{\rho_i}$$

$$y_{i+1} = y_i + \rho_i \sin(\Delta\theta_i)$$

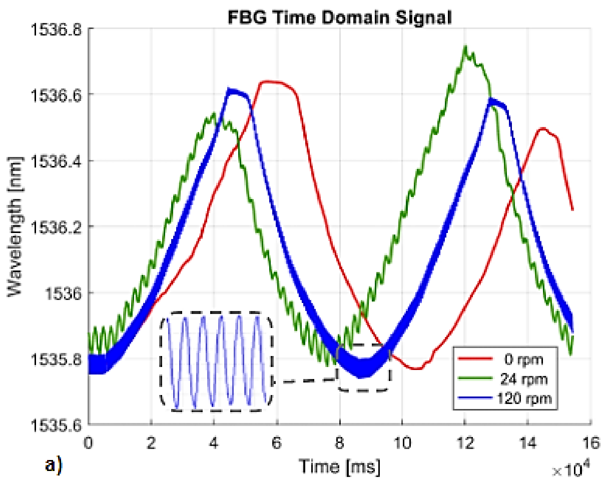
$$z_{i+1} = z_i + \rho_i (1 - \cos(\Delta\theta_i))$$

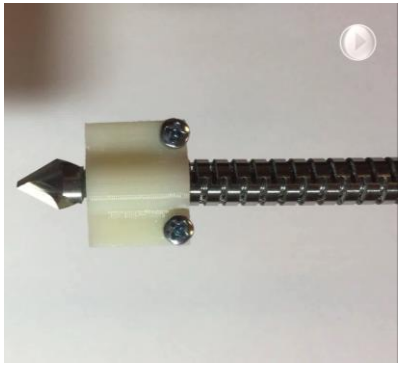




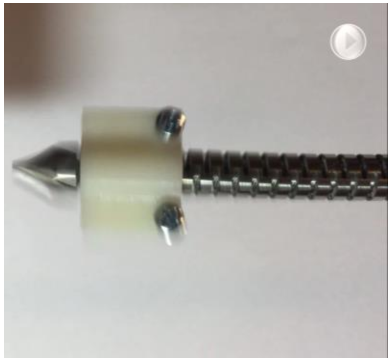
Liu et al. Sensor 2015; S. Sefaty, **F. Alambeigi**, et al., ISMR2018; S. Sefaty, R. J. Murphy, **F. Alambeigi**, et al., IROS 2018

Shape Sensing In the Presence of a Rotating Cutting Tool

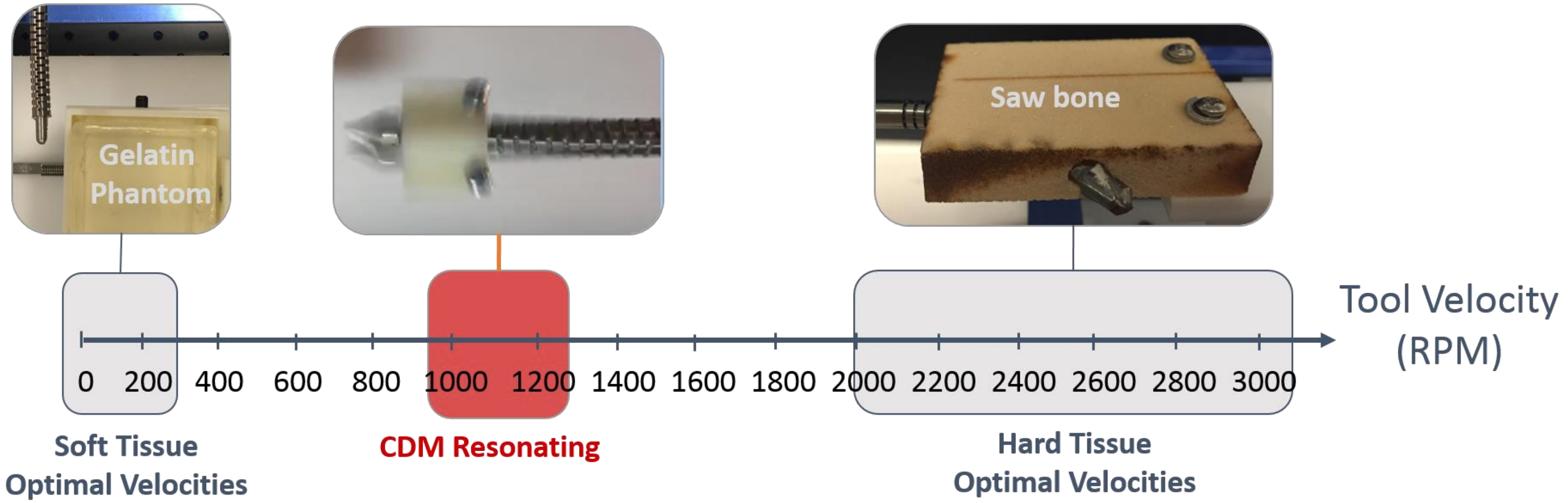




Tool Velocity **80** RPM

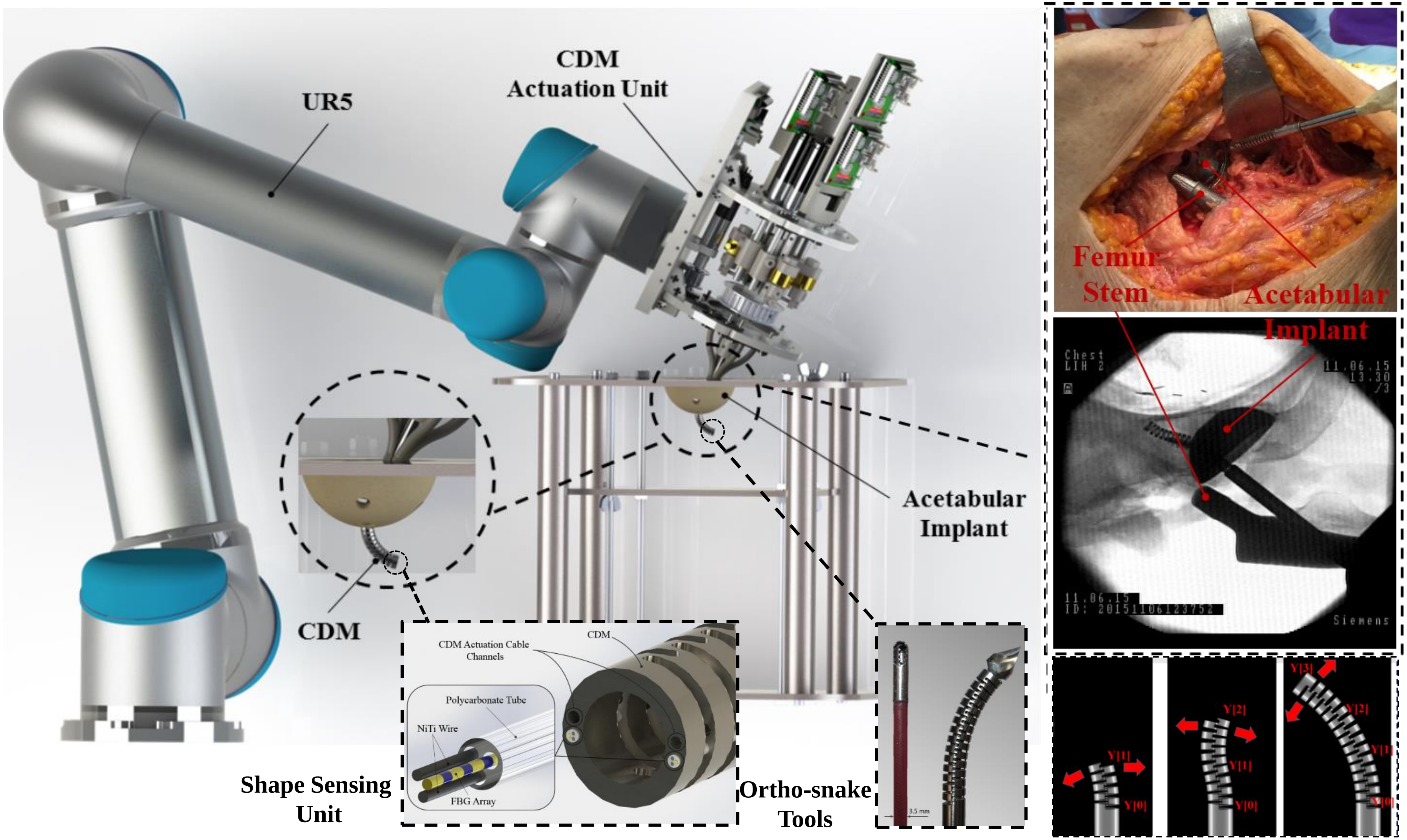


Tool Velocity **1050** RPM
(Resonation of Tool and CM)



S. Sefaty, **F. Alambeigi**, et al., ISMR2018

Hybrid Redundant Surgical System (6+2 DoF)



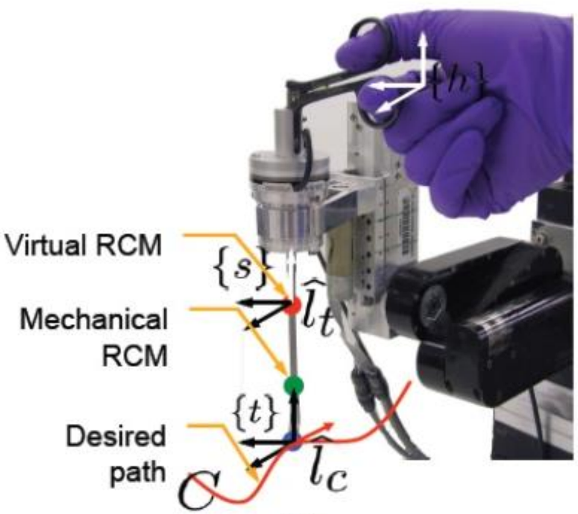
Constrained Concurrent Control of the Hybrid Redundant System

Assumptions:

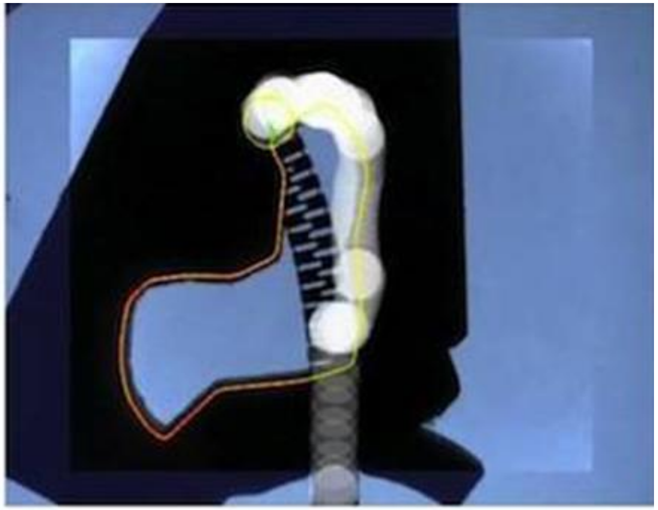
1. The whole Flexible region of the CDM is inside the patient's body
2. No external force is applied to the tip of the CDM

Constraint: Effect of screw holes on Degrees of Freedom

- ➢ No mechanical remote center of motion (RCM) for UR5



(a)

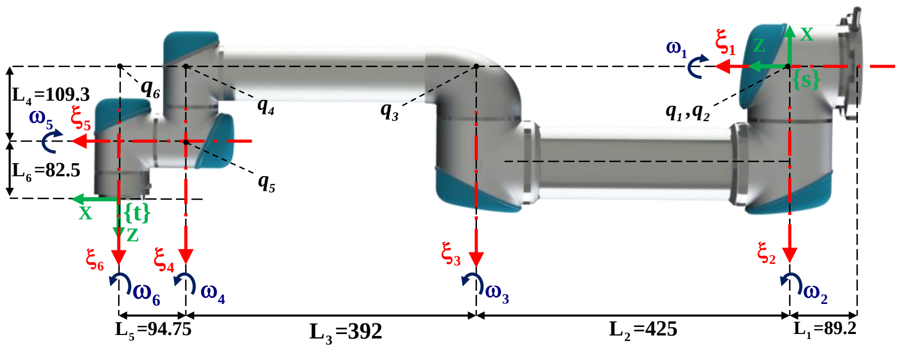


(b)

Fig (a). A. Kapoor, M. Li, and R. H. Taylor, ICRA 2006". Fig (b). R.J. Murphy, et al, ICRA 2013.

Kinematics of the Hybrid Redundant Surgical System

- To apply the proposed method for redundancy resolution of a robotic system, Jacobian of the system as well as the constraints need to be defined.

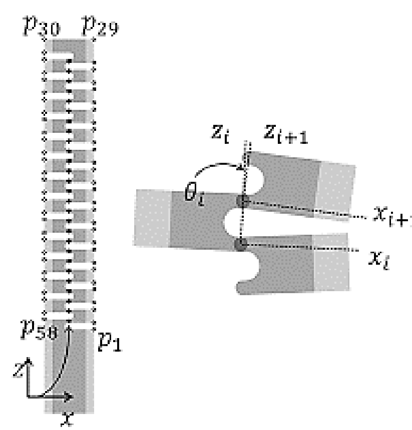


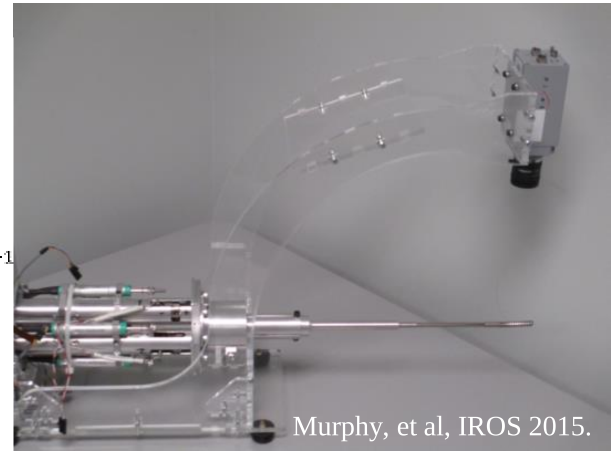
$$\underset{\Delta\theta}{\operatorname{argmin}} \ \|J(\theta)\Delta\theta - \Delta x\|_2^2 + \lambda\|\Delta\theta\|_2^2$$

$$Subject\ to\ \ A\,\Delta\theta \le b$$

$$J_{Combined} = [J_{UR5} \quad J_{CDM}],$$
$$J_{UR5} \in R^{6\times 6}\ and\ J_{CDM} \in R^{6\times 2}$$

$$\dot{x}_{CDM\ tip}^{UR5\ base} = J_{Combined}\ \dot{\theta}_{Combined}$$





Murphy, et al, IROS 2015.

F. Alambeigi, et al. *American Control Conference, 2018;* **F. Alambeigi**, et al. *EMBC2014; P. Wilkening,* ***F. Alambeigi****, et al, RAL 2017*

Defined Constraints

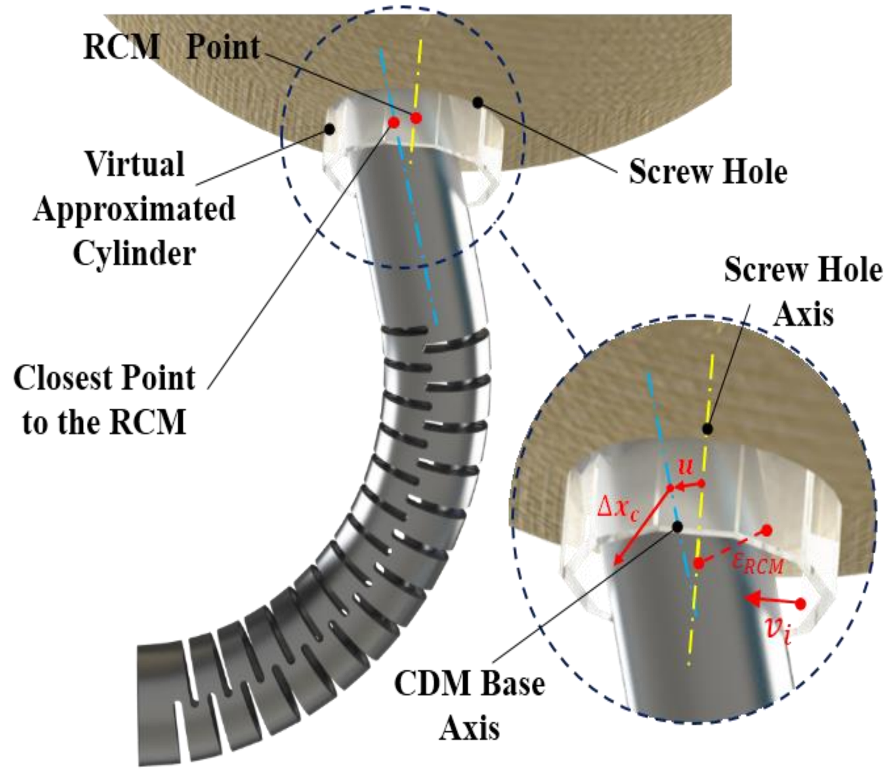
➢ The RCM constraint:

- ✓ ensures movements of the CDM base are confined in a ***virtual cylinder*** around the screw hole axis.
- ✓ it prevents any collision between the CDM base and the screw hole edges during pivoting around the center of the hole.

$$\underbrace{\begin{bmatrix} v_1 \\ \vdots \\ v_m \end{bmatrix}}_{A_1} . \Delta x_c \leq \underbrace{\begin{bmatrix} \varepsilon_{RCM} + v_1 . u \\ \vdots \\ \varepsilon_{RCM} + v_m . u \end{bmatrix}}_{b_1}$$

$$\Delta x_c = J_{closest\ point} . \Delta\theta_{UR5};$$

$$A_1 \in R^{m\times 7}, \Delta\theta_{UR5} \in R^{6\times 1}$$



F. Alambeigi, et al. *American Control Conference, 2018*

Defined Constraints

➢ The joint limits constraint:

$$\underbrace{\begin{bmatrix} I_6 & 0 \\ 0 & 1 \\ -I_6 & 0 \\ 0 & -1 \end{bmatrix}}_{A_2} . \Delta\theta \leq \underbrace{\begin{bmatrix} \Delta\theta_{UR5_{Upper}} \\ 9\ mm - \theta_{CDM} \\ -\Delta\theta_{UR5_{Lower}} \\ \theta_{CDM} \end{bmatrix}}_{b_2}$$

where $\Delta\theta \in R^{7\times1}, A_2 \in R^{14\times7}$.

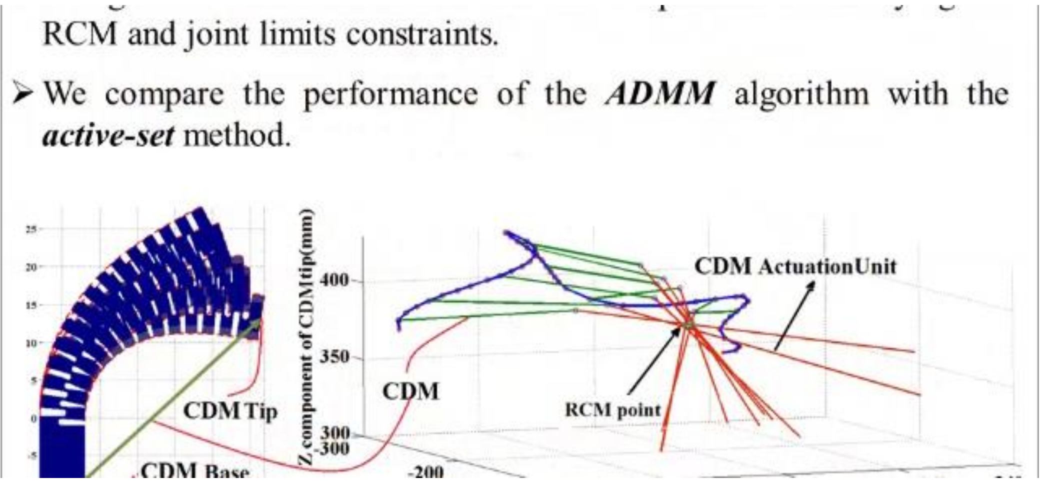
➢ The combined constraint matrix :

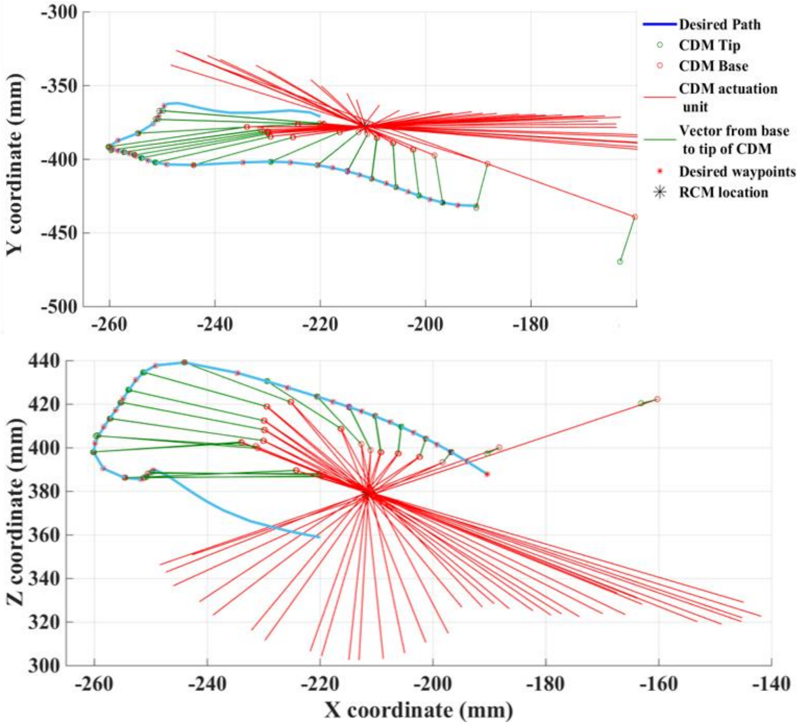
$$\underbrace{\begin{bmatrix} A_1 & 0 \\ & A_2 \end{bmatrix}}_{A} . \Delta\theta \leq \underbrace{\begin{bmatrix} b_1 \\ b_2 \end{bmatrix}}_{b}, \ \Delta\theta \in R^{7\times1}.$$

F. Alambeigi, et al. *American Control Conference, 2018*

Trajectory Tracking with Constant Parameters

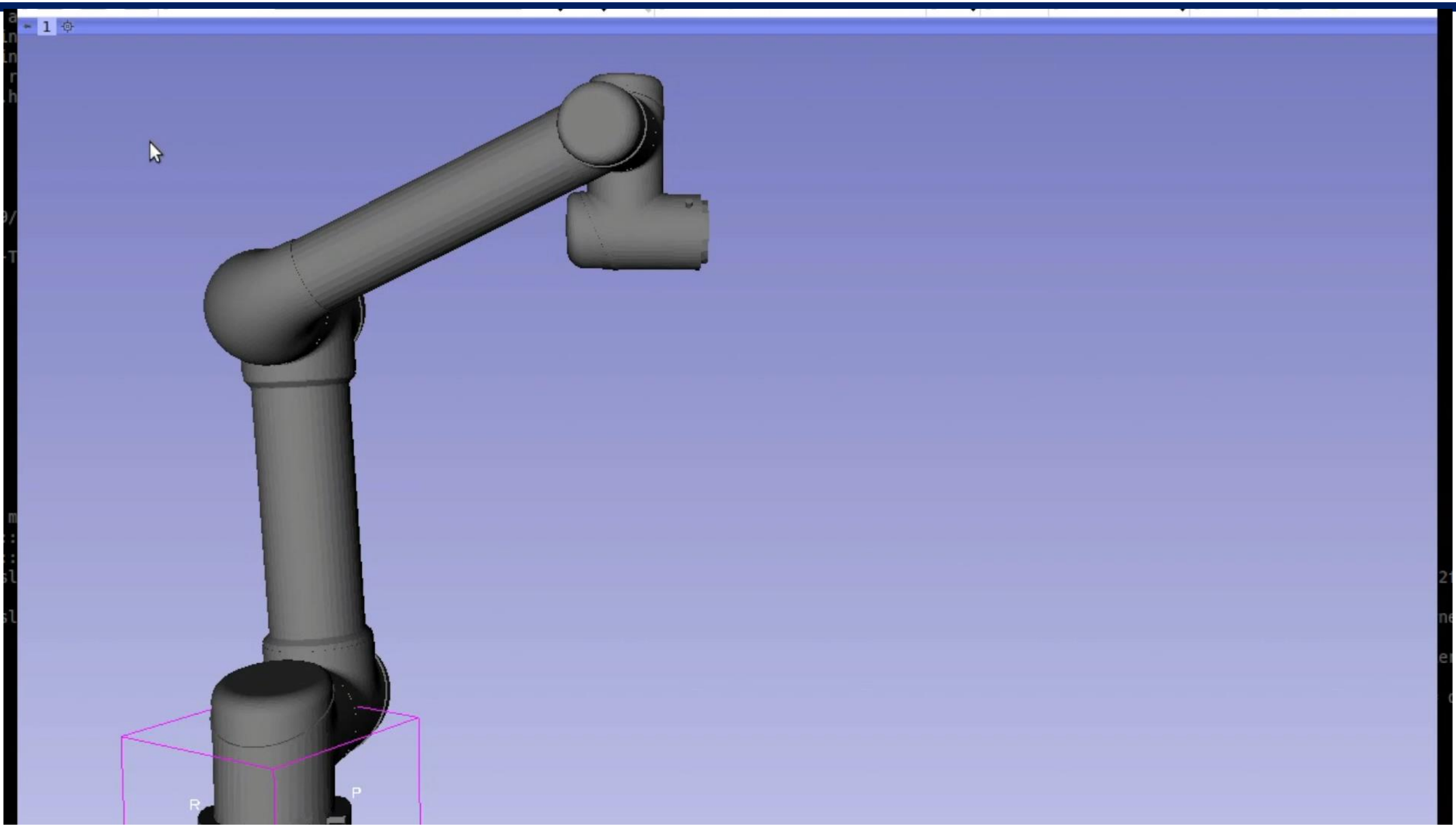
- The goal of these simulations is to track a path while satisfying the RCM and joint limits constraints.
  - $\lambda = 2e^{-4}, MTE \leq 0.5\, mm,$ and $RCME \leq 0.5\, mm.$





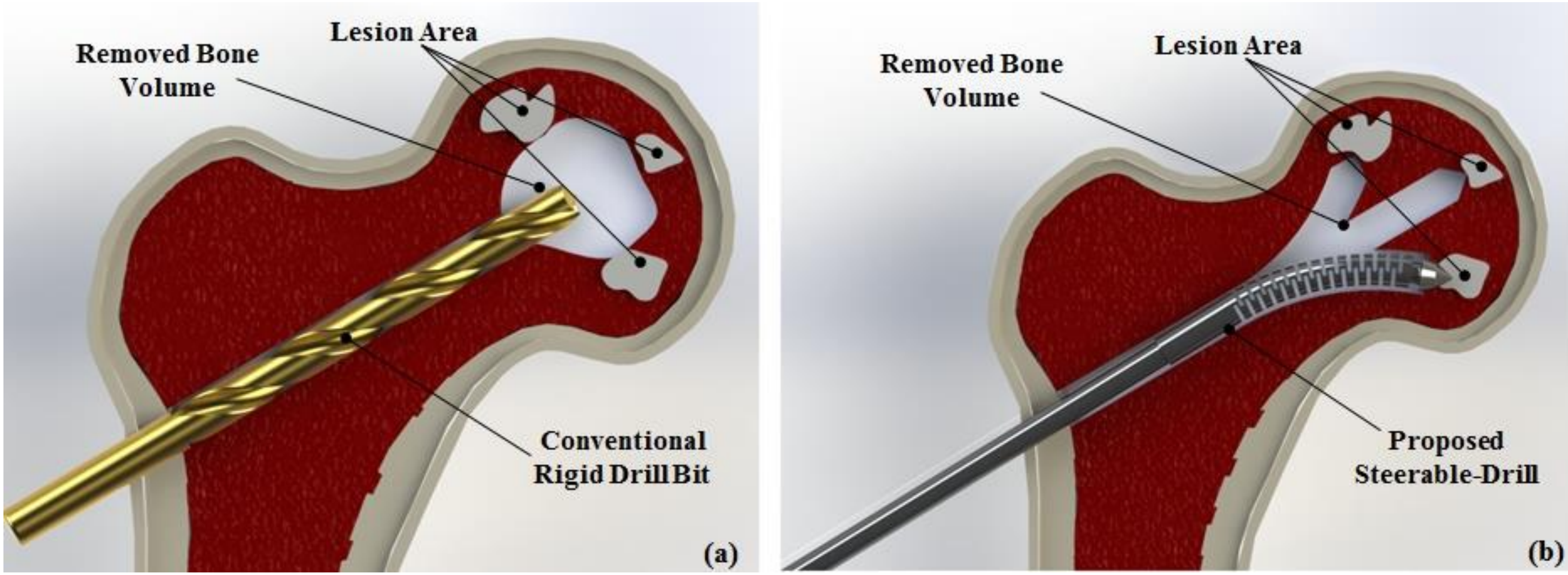
F. Alambeigi, et al. *American Control Conference, 2018;* ***F. Alambeigi*** *et al. EMBC 2014; P. Wilkening, F. Alambeigi et al. Robotics and Auromation Letter 2017.*

Milling Simulated Bone Material with FBG Feedback



Slide is courtesy of Rachel Hegeman.

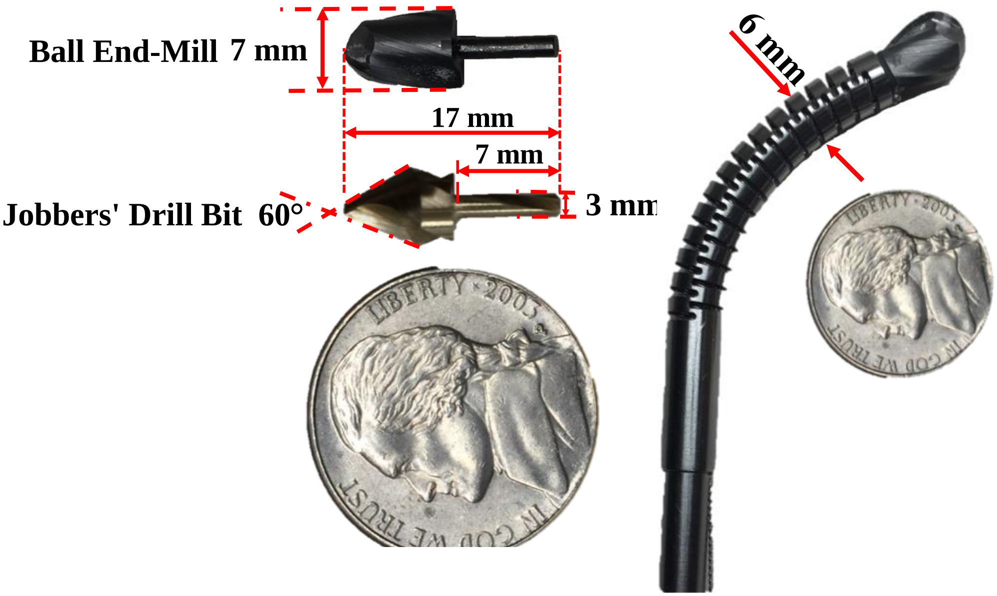
Core decompression of Femoral Osteonecrosis

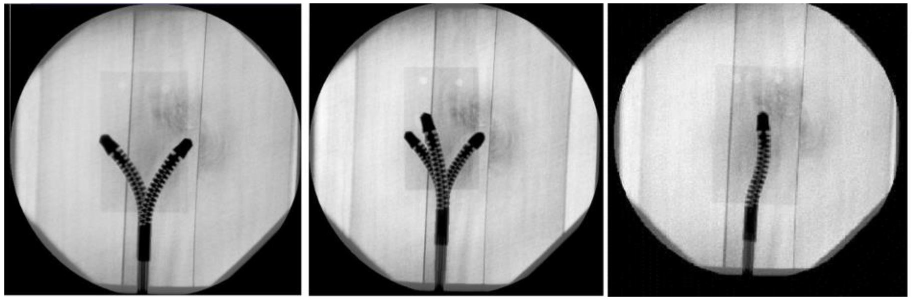


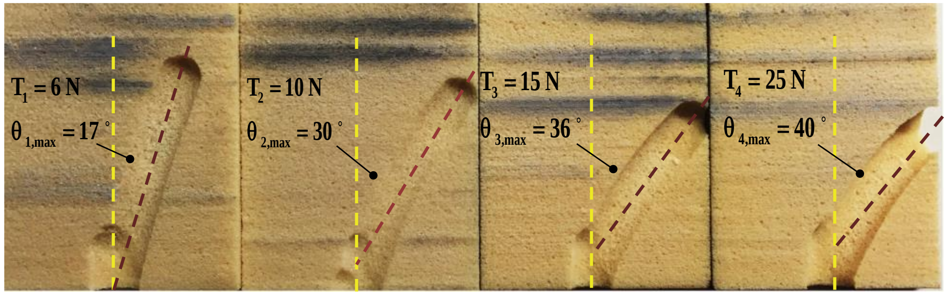
- Core decompression is a procedure too reduce the pressure in the femoral head and restore the blood supply in the dead bones.
- Drilling either <u>a hole with 8 to 12 mm</u> diameter <u>or multiple 3 mm holes.</u>
- Due to <u>**individual variation**</u> in distributions, sizes and shapes of the necrotic lesion, utilizing <u>**conventional rigid tools**</u> limit accessibility and debridement of the entire lesion.

F. Alambeigi, et al. "*A Curved Drilling Technique for Core Decompression of Femoral Head Osteonecrosis*" ***Robotics and Automation Letter/ICRA 2017.***

Core decompression of Femoral Osteonecrosis





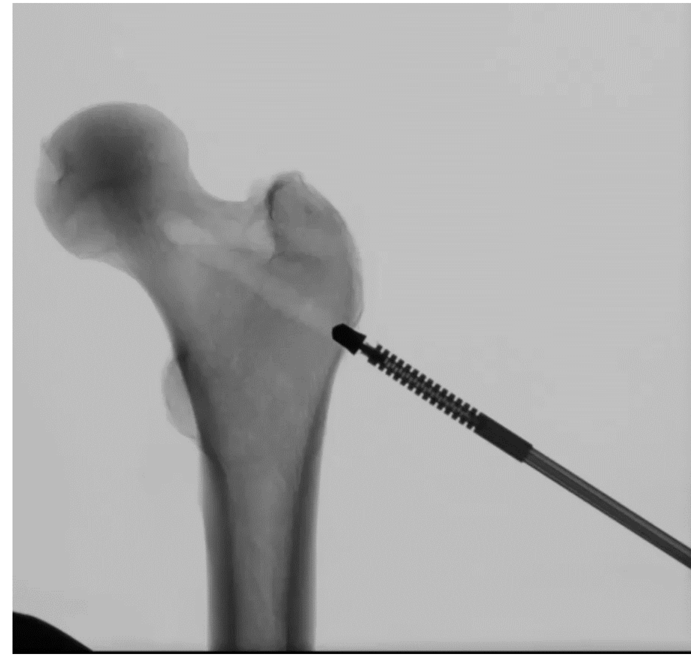


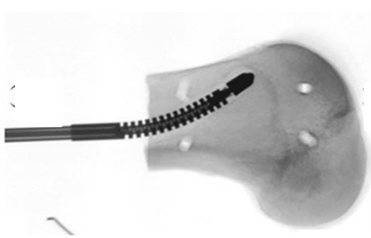
C- and S-Shape, and branch Curved Drilling

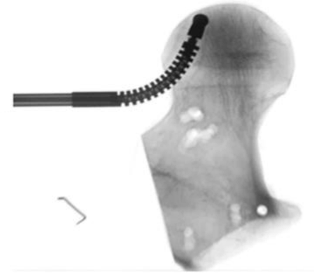
Cross-section of the samples

F. Alambeigi, et al. “*A Curved Drilling Technique for Core Decompression of Femoral Head Osteonecrosis*” ***Robotics and Automation Letter/ICRA 2017.***

Curved Drilling Feasibility on Human Cadavers

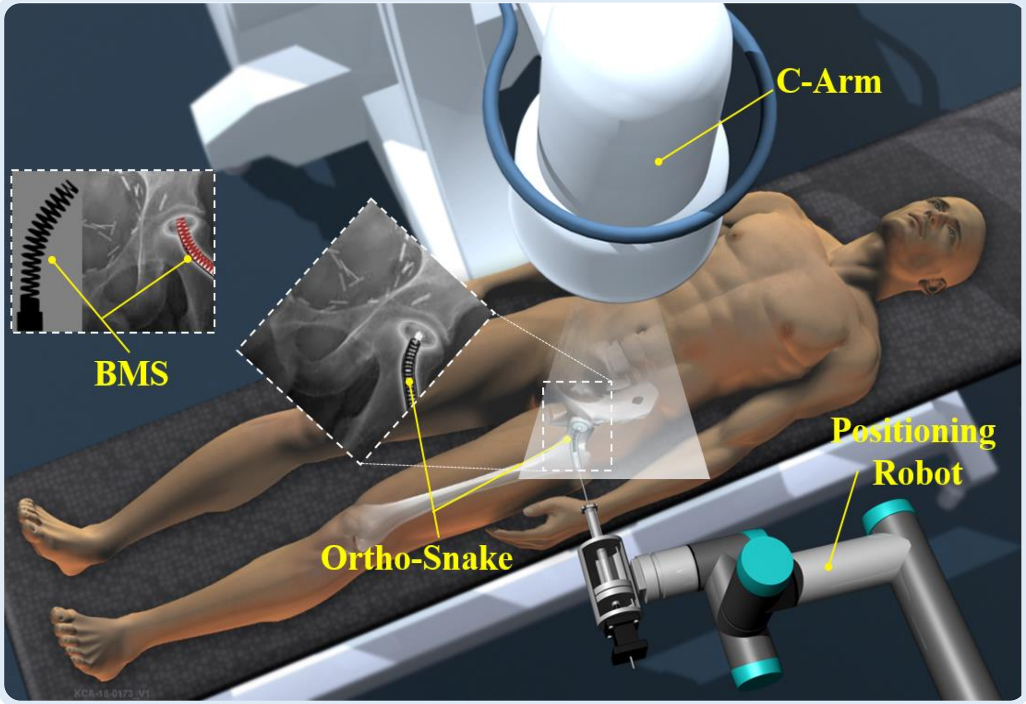






Internal Fixation of Bone Fractures Using a Bendable Medical Screw

- Internal fixation uses a **rigid cannulated screw** to fix fragments of a fractured bone together and expedite the healing process.
- Complications:
  - ✓ improper fracture healing,
  - ✓ lengthy procedure time and subsequently high radiation.
- Limitations:
  - ✓ The rigidity of the screw,
  - ✓ geometry of the fractured anatomy (e.g. femur and pelvis),
  - ✓ patient's age (Osteoporotic bone)



We propose **Curved Drilling** with ortho-snake and using a **novel bendable medical screw** (BMS) for fixating the fractures.

F. Alambeigi, et al. "*Inroads Toward Robot-Assisted Internal Fixation of Bone Fractures Using a Bendable Medical Screw and the Curved Drilling Technique*" ***in Biorob 2018. (Finalist of the Best Paper Award)***

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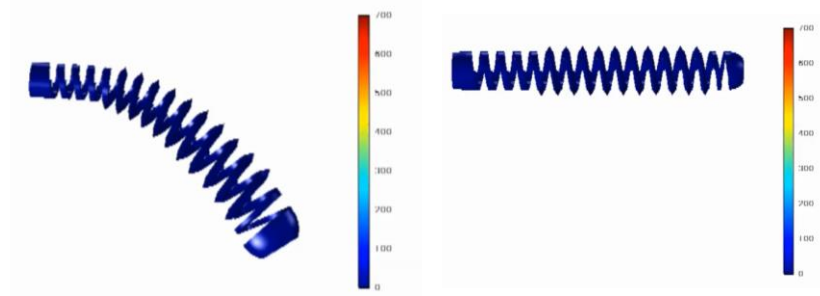
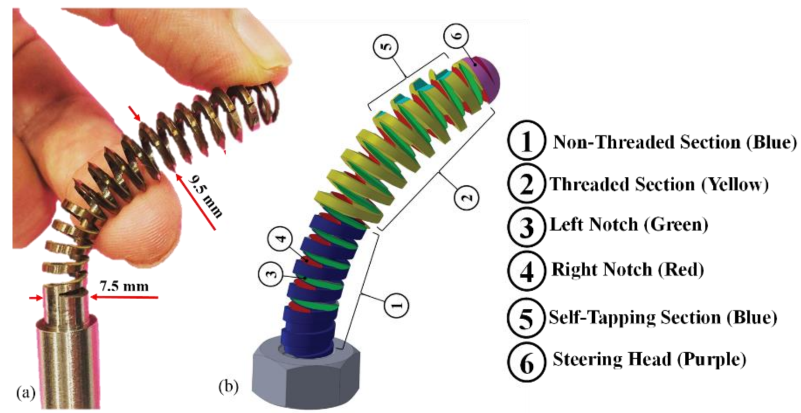
Internal Fixation of Bone Fractures Using a Bendable Medical Screw



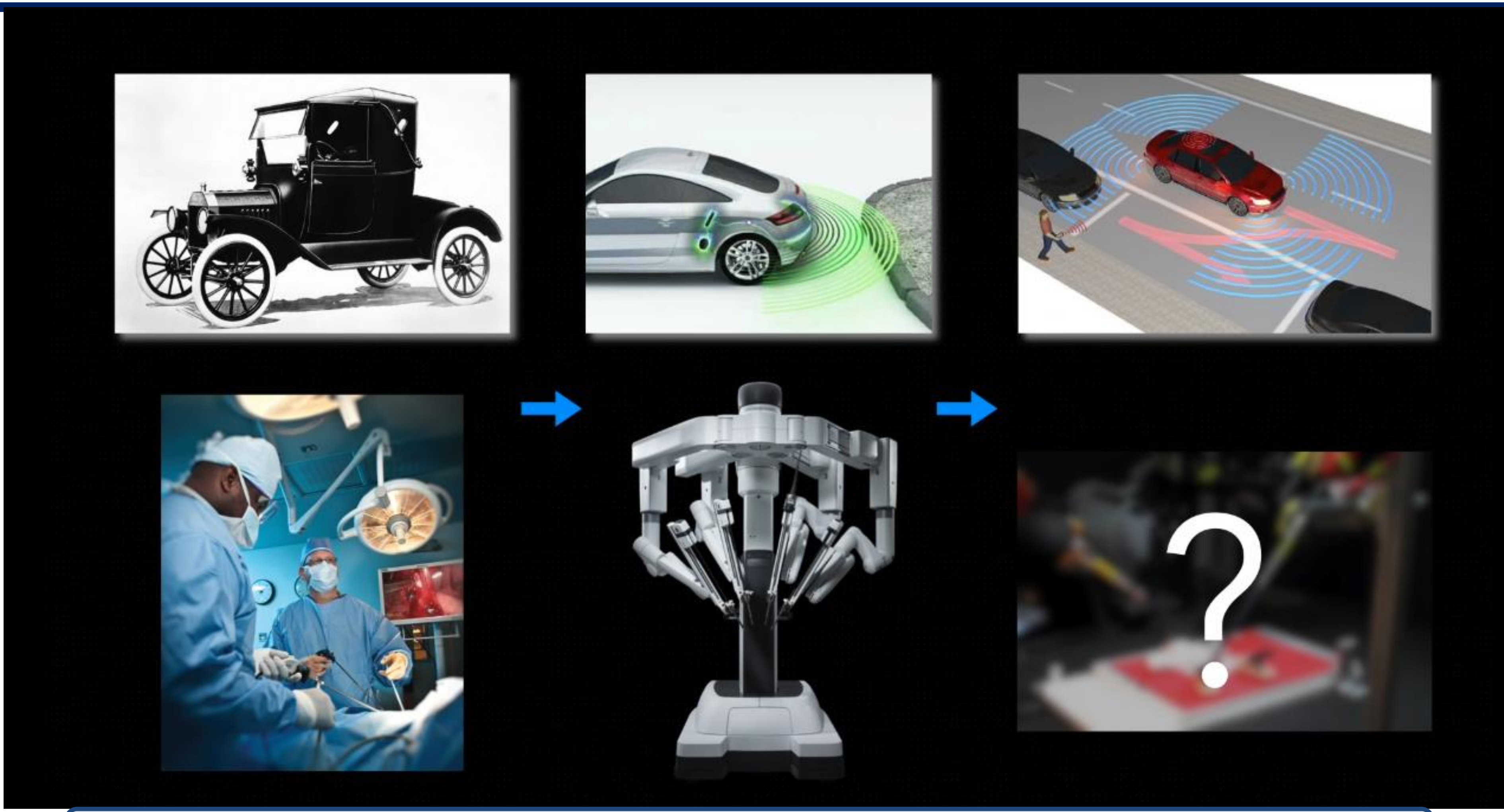
Stress Distribution During Bending and Fastening



Conceptual Design and Fabricated BMS

F. Alambeigi, et al. "*Inroads Toward Robot-Assisted Internal Fixation of Bone Fractures Using a Bendable Medical Screw and the Curved Drilling Technique*" ***in Biorob 2018. (Finalist of the Best Paper Award)***

Motivation: Need for Autonomous Surgical Systems



Robots can perform <u>certain surgical tasks</u> autonomously under the <u>supervision</u> of the surgeon

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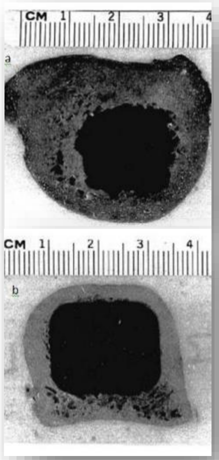
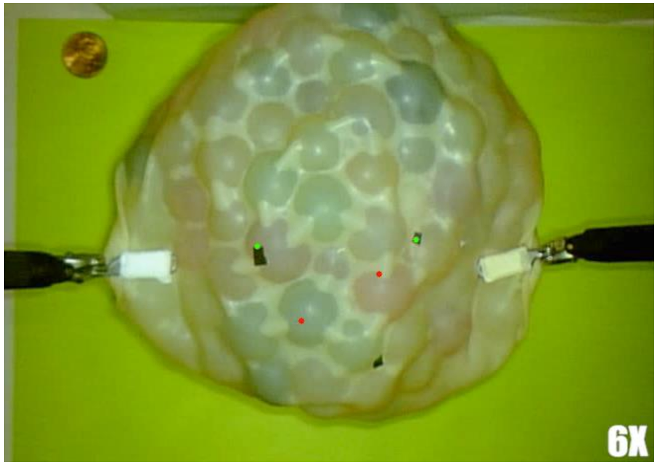
Motivation: Manipulation of Deformable Objects



Autonomous Surgery on Rigid Bones: ROBODOC (1992) [1]

Tele Operation with Intuitive Surgical daVinci Xi- Hysterectomy

Human vs. **Robot**



[1] Paul HA, et al., Clin Orthop Relat Res. 1992.

Autonomous Medical Robotics Using Continuum Robots

- **Tele-Operation of Different Types of Continuum Robots and Flexible Forceps**

ISI

Vanderbilt University

JHU

- **Autonomous Control of Continuum Robots in interaction with Tissues**

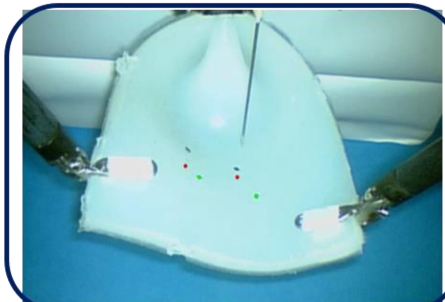
Vanderbilt University

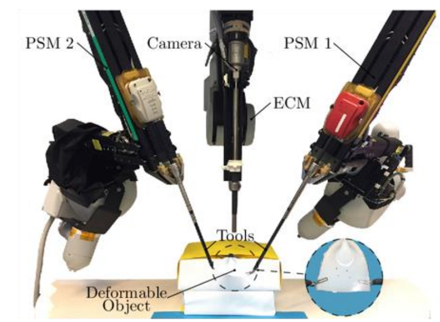
Children's Hospital Boston

CMU

Model Independent Manipulation of Deformable Objects

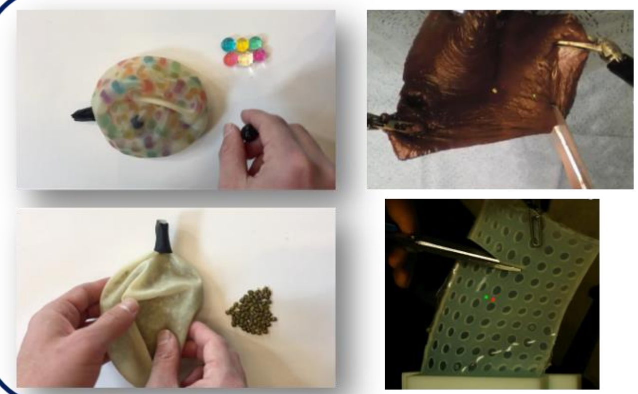
Needle Insertion Using Target manipulation technique

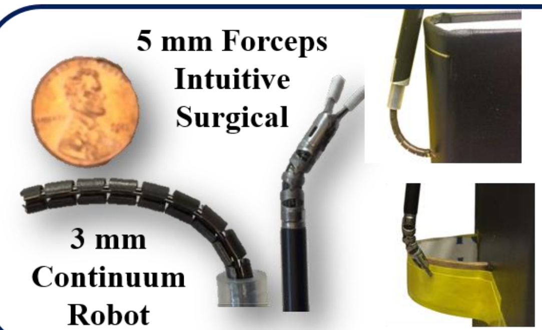




da Vinci Research Kit 2 PSM and 1 ECM

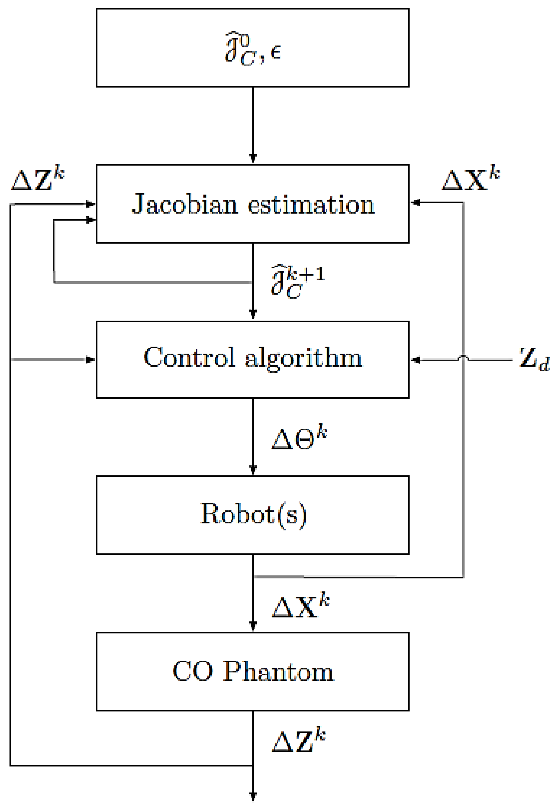
Deformable Phantoms with variable mass distribution





F. Alambeigi, Zerui Wang, et al. "*Smart Autonomous Unknown Deformable Object Manipulation Using the da Vinci research Kit from Soft Tissues to Continuum Robots Manipulation*" ***Best Innovation Prize, Hamlyn Surgical Challenge, 2017.***

Model Independent Manipulation of Deformable Objects



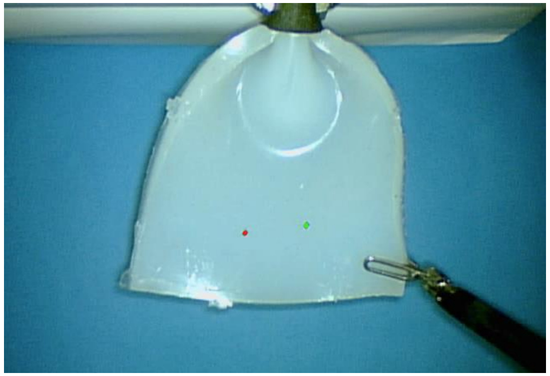
$$\hat{\mathfrak{J}}_C^{k+1} = \hat{\mathfrak{J}}_C^{k} + \alpha \frac{\Delta \mathbf{Z} - \hat{\mathfrak{J}}_C^{k} \Delta \mathbf{X}}{(\Delta X)^{\mathsf{T}}(\Delta X)} (\Delta X)^{\mathsf{T}}$$

$$\begin{aligned} \underset{\Delta\boldsymbol{\theta}(t)}{\arg\min} \quad & \left\| \hat{\mathfrak{J}}_C \mathfrak{J}_R \Delta\Theta^k - \widetilde{\Delta \mathbf{Z}}^k \right\|_2^2 \\ \text{s.t.} \quad & \mathbf{A}^k \Delta\Theta^k \leq \mathrm{b}^k, \\ & \Delta\Theta^k \leq \Delta\Theta_{\max} \end{aligned}$$

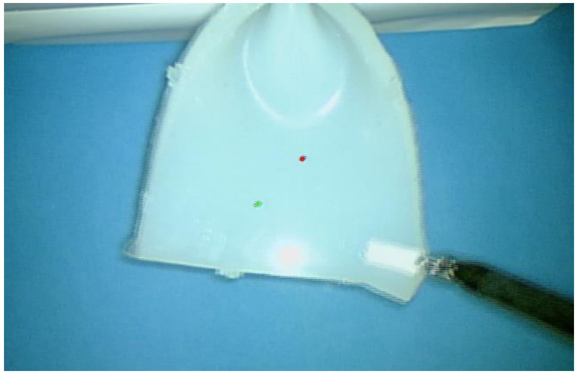
Homogeneous Shape and Mass Distribution Silicon Rubber

- **Goal: Overlaying the Green Point(s) in the image to the Red Point(s)**

Constraint-Free Manipulation Task

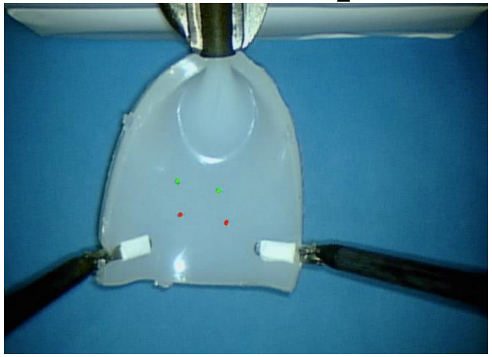


Constraint-Free Folding Task



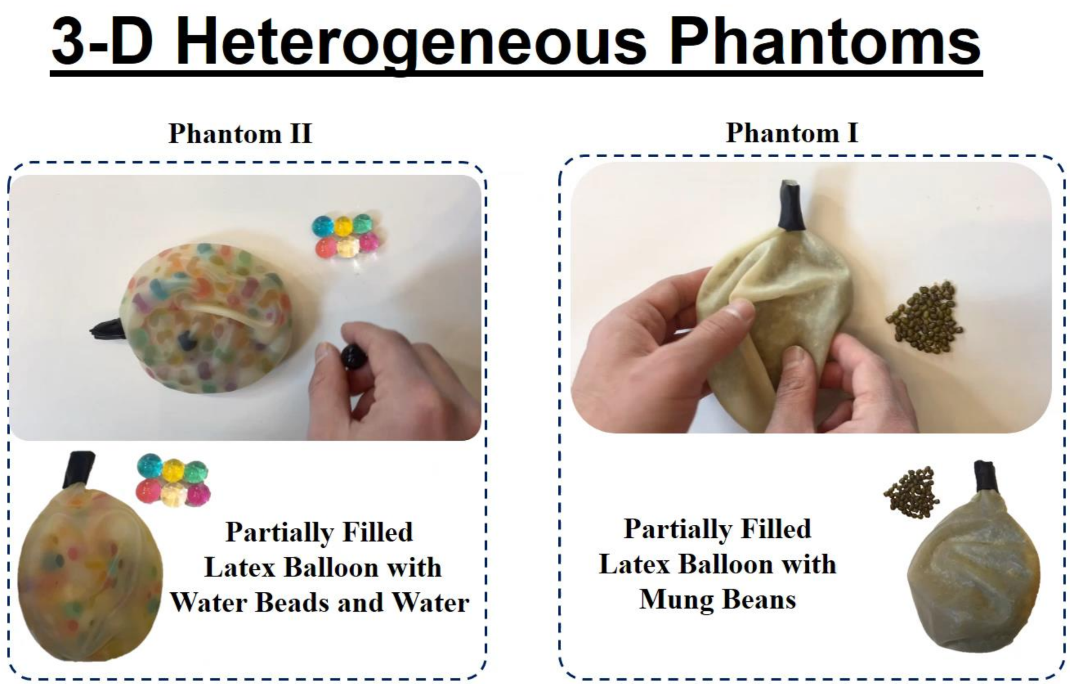
Constrained Manipulation in the Image Space

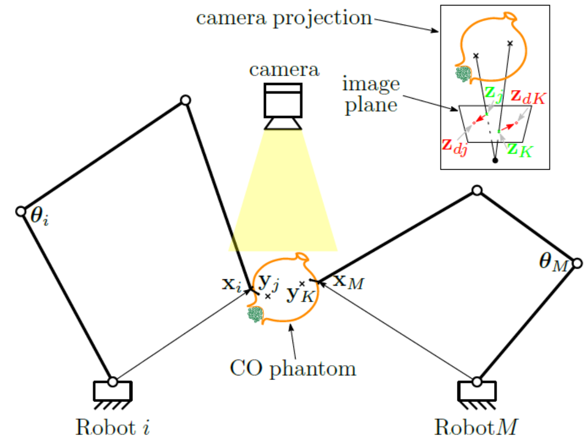
Collaborative Manipulation Task

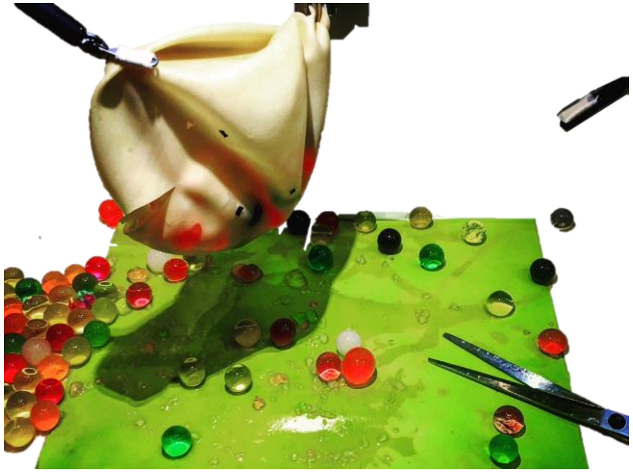


F. Alambeigi, Zerui Wang, et al. "*Smart Autonomous Unknown Deformable Object Manipulation Using the da Vinci research Kit from Soft Tissues to Continuum Robots Manipulation*" ***Best Innovation Prize, Hamlyn Surgical Challenge, 2017.***

Model Independent Manipulation of Heterogeneous Objects

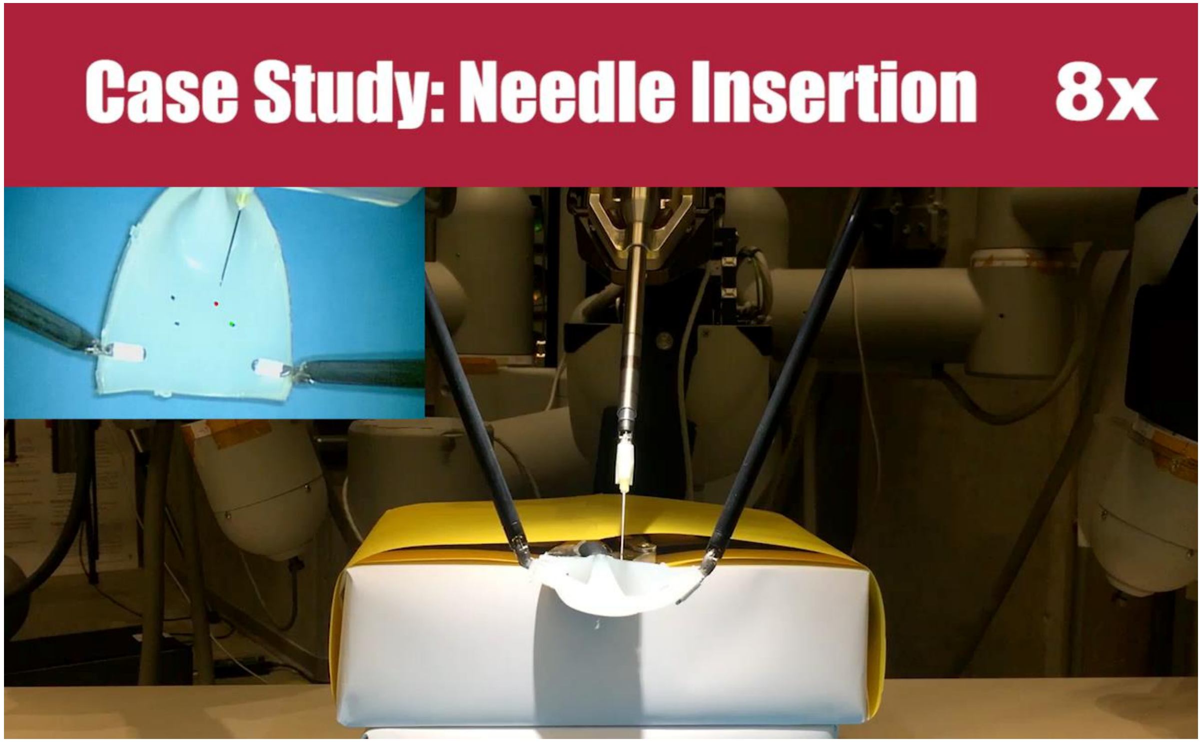


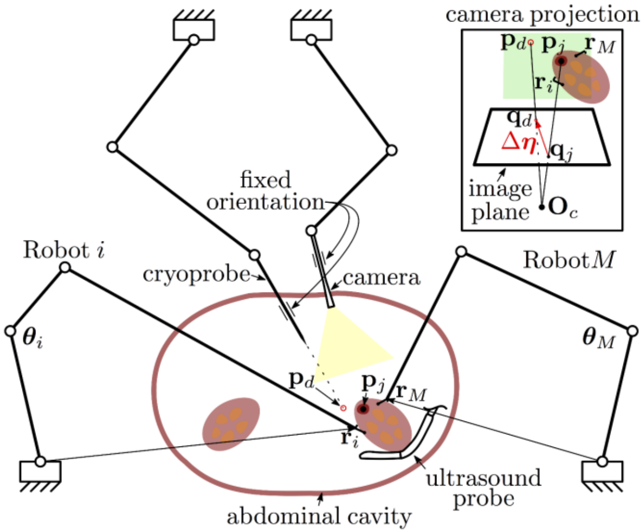




F. Alambeigi, Zerui Wang, et al. "*A Robust Data-Driven Approach for Real-Time Learning and Manipulation of Unmodeled 3-D Heterogeneous Compliant Objects*", ***Robotics and Automation Letter/IROS 2018.***

Indirect Tissue Manipulation for Needle Insertion





- **Advantage:** Avoiding unwanted perforation or bleeding.
- **Application:** Laparoscopic biopsy of soft tissue organs (e.g. liver or kidney)

F. Alambeigi, Zerui Wang, et al. "*Toward Semi-Autonomous Cryoablation of Kidney Tumors via Model-Independent Deformable Tissue Manipulation Technique*" ***Annals of Biomedical Engineering (ABME), 2018.***

Indirect Tissue Manipulation for Needle Insertion

Indirect Manipulation
Of a Lamb Liver With External Disturbances

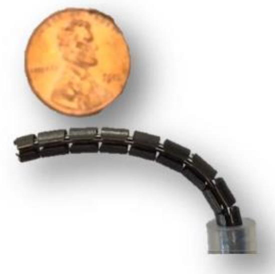
Collaborative Manipulation
Of a Lamb Kidney

F. Alambeigi, Zerui Wang, et al. "*Toward Semi-Autonomous Cryoablation of Kidney Tumors via Model-Independent Deformable Tissue Manipulation Technique*" ***Annals of Biomedical Engineering (ABME), 2018.***

Model-Independent Control of CMs in Unknown Constrained Environments

Continuum Manipulators

5 mm DeBAKEY Forceps, Intuitive Surgical Inc.



3 mm Continuum Manipulator designed for head and neck surgery

F. Alambeigi, Zerui Wang, et al. "*A Versatile Data-Driven Framework for Model-Independent Control of Continuum Manipulators Interacting with Obstructed Environments with Unknown Geometry and Stiffness*" ***Minor Revision*, *International Journal of Robotic Research (IJRR) 2018.***

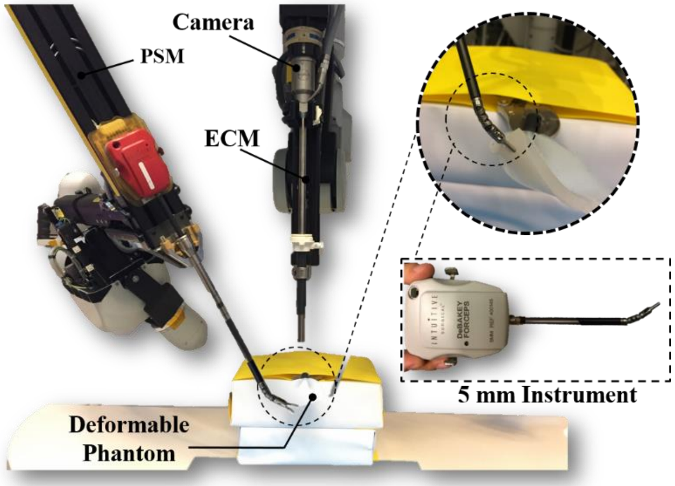
Data-Driven Manipulation of unknown Tissues Using Unmodeled CMs

Experiment I

The ACM-DTM with the **homogeneous phantom**

Goal:

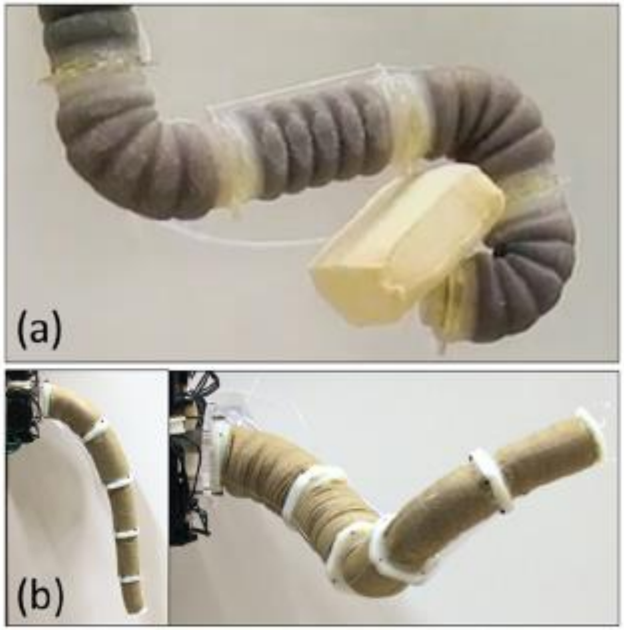
Indirect Manipulation of phantom with the CM to overlay the **Green Point** on the **Red Point**



F. Alambeigi, Zerui Wang, et al. "*A Robust Data-Driven Approach for Real-Time Learning and Manipulation of Unmodeled 3-D Heterogeneous Compliant Objects*", ***Revised and Resubmitted to Robotics and Automation Letter/ICRA 2019.***

Stiffness Tuning

- A common design trade-off for continuum manipulators involves maintaining stiffness and maximizing payload carrying.
- **On-demand stiffness tuning** is one approach to take the advantages of both stiffness and Compliance
- Several techniques such as **reversible jamming of granular media** for achieving variable stiffness have been proposed in the literature.



Cheng et al, in ICRA, 2012.

Cianchetti , et al, Soft Robotics, vol. 1, 2014.

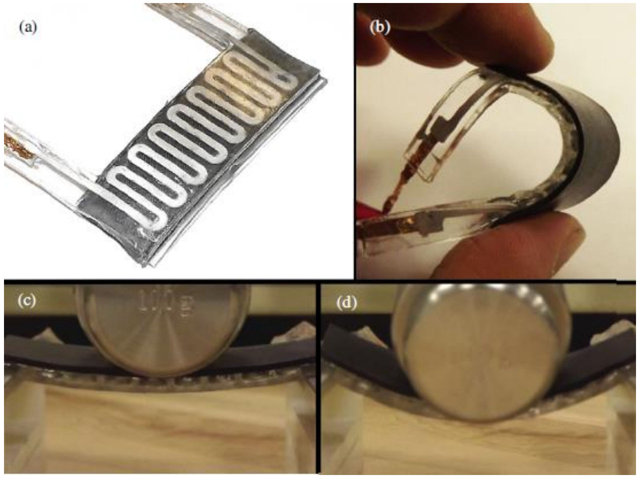
Variable Stiffness Continuum Manipulator Using Field's Metal

- We use **Field's metal** to transform the continuum manipulator phase.

- To overcome deficiencies of the current stiffness changing approaches we considered following design criteria for our continuum manipulator:

    1) under-actuation
    2) compliancy, safety, and dexterity;
    3) large payload capacity;
    4) Having tool channel;
    5) Quick change of stiffness (less than 5 secs);
    6) easy fabrication;
    7) energy and cost efficiency.

Video :"Metal Meltdown", (www.youtube.com/user/brainiac75).



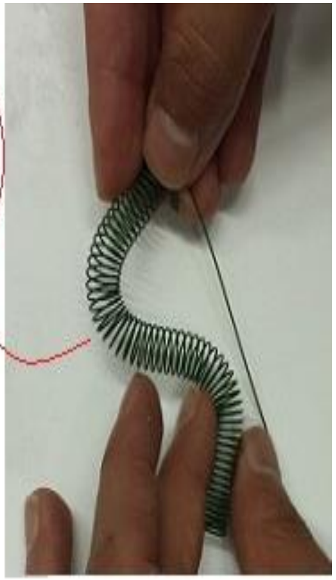
W. Shan, et al, Journal of Smart Mater. Struct. 22 (2013).

Proposed design and Working Principle

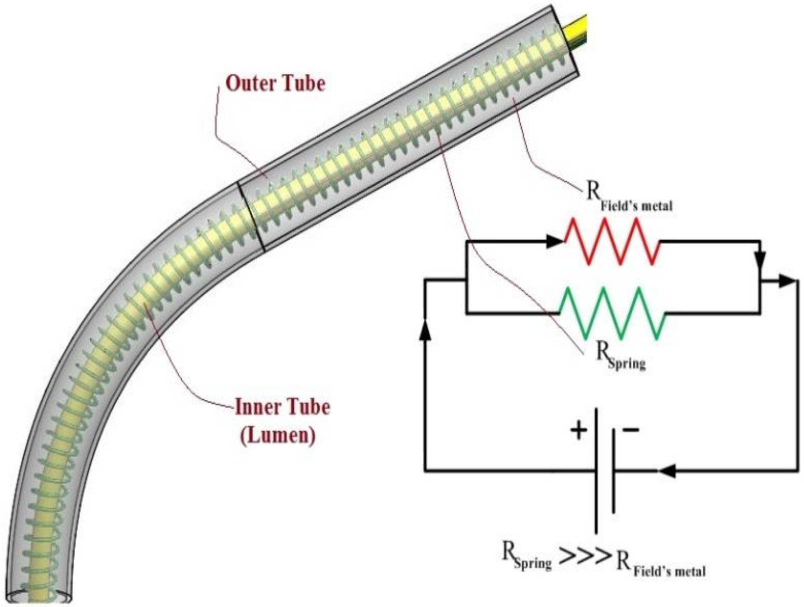
Field's metal layer around coated Spring

Schematics of the proposed continuum manipulator

Soft mode of the continuum manipulator



PTFE coated Spring

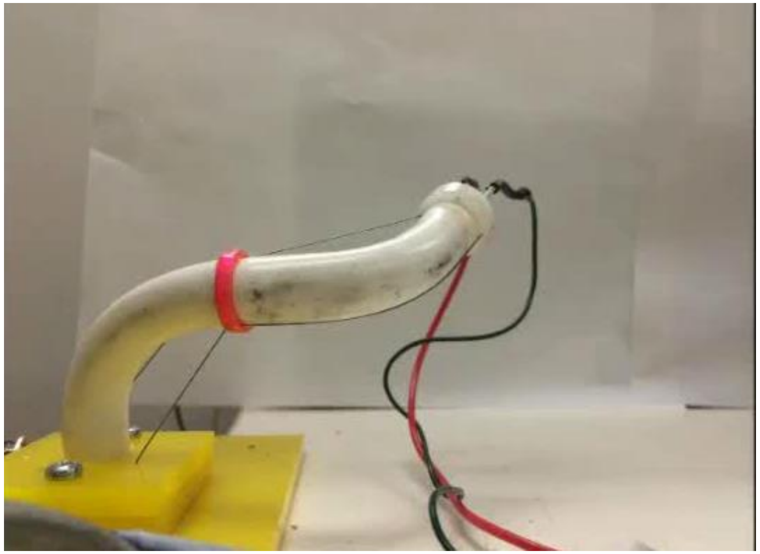


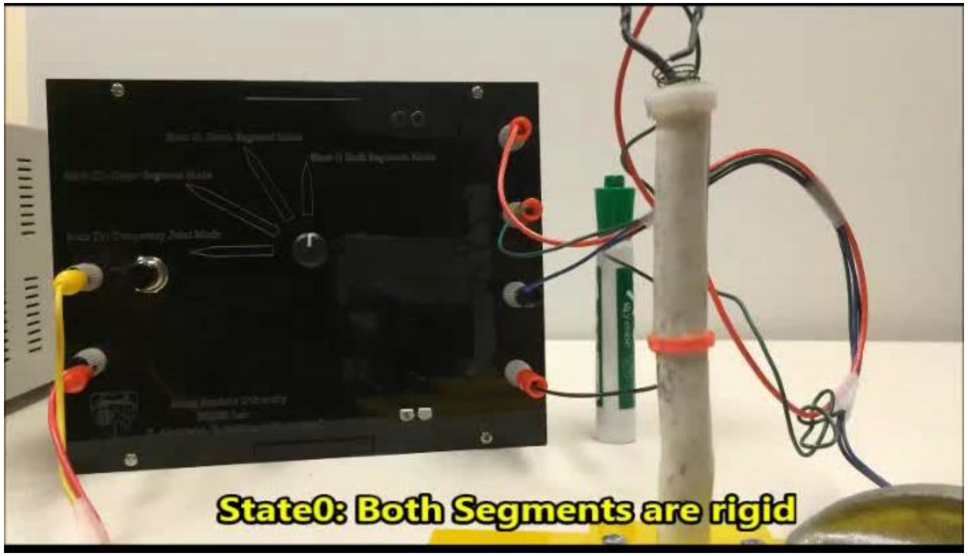
Field's metal is significantly electrically more conductive than the spring

F. Alambeigi, et al, ICRA 2016.

Performance Evaluation Experiments

- **Dexterity test:**





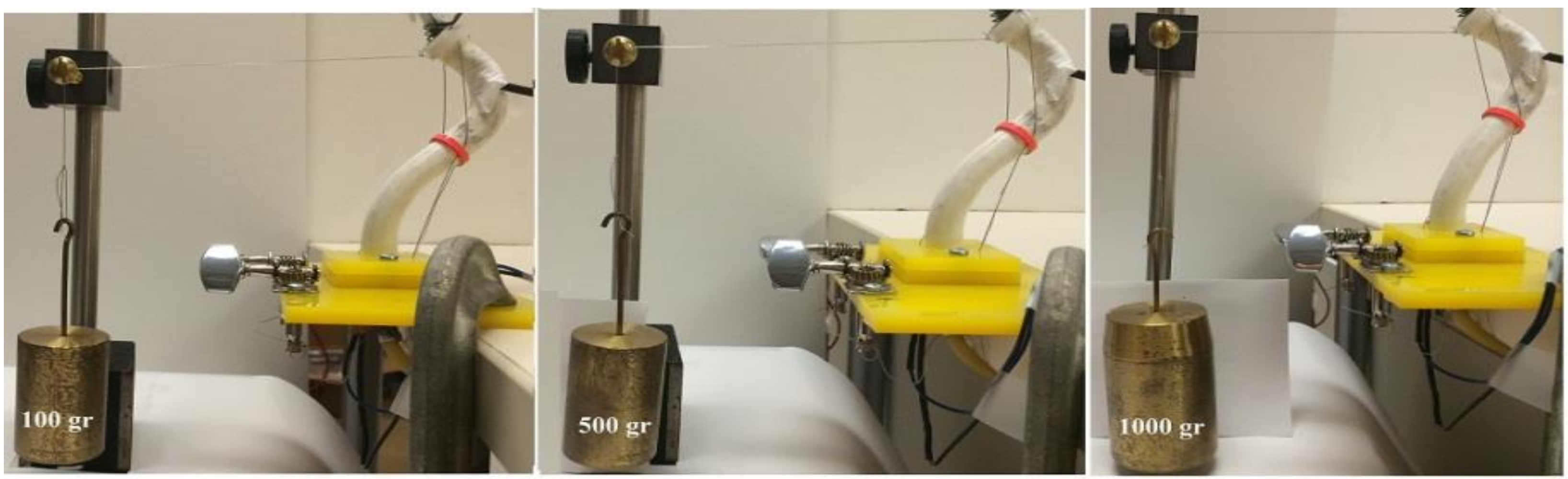
Complex shapes generated by basic configurations of the robot.

Basic configurations of the robot.

F. Alambeigi, et al, ICRA 2016.

Performance Evaluation Experiments

- **Payload capacity experiment:**
  Using 20gr of Field's metal, the 12 cm long, and 13 mm diameter PC-CM could withstand 1000 gr force in solid state.



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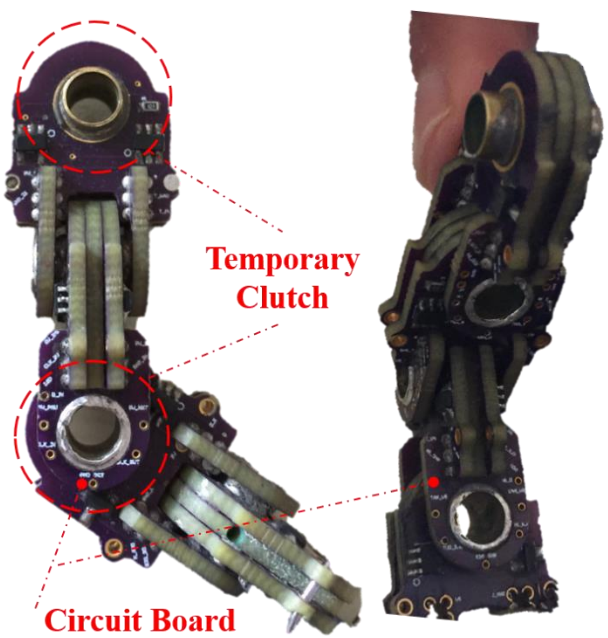
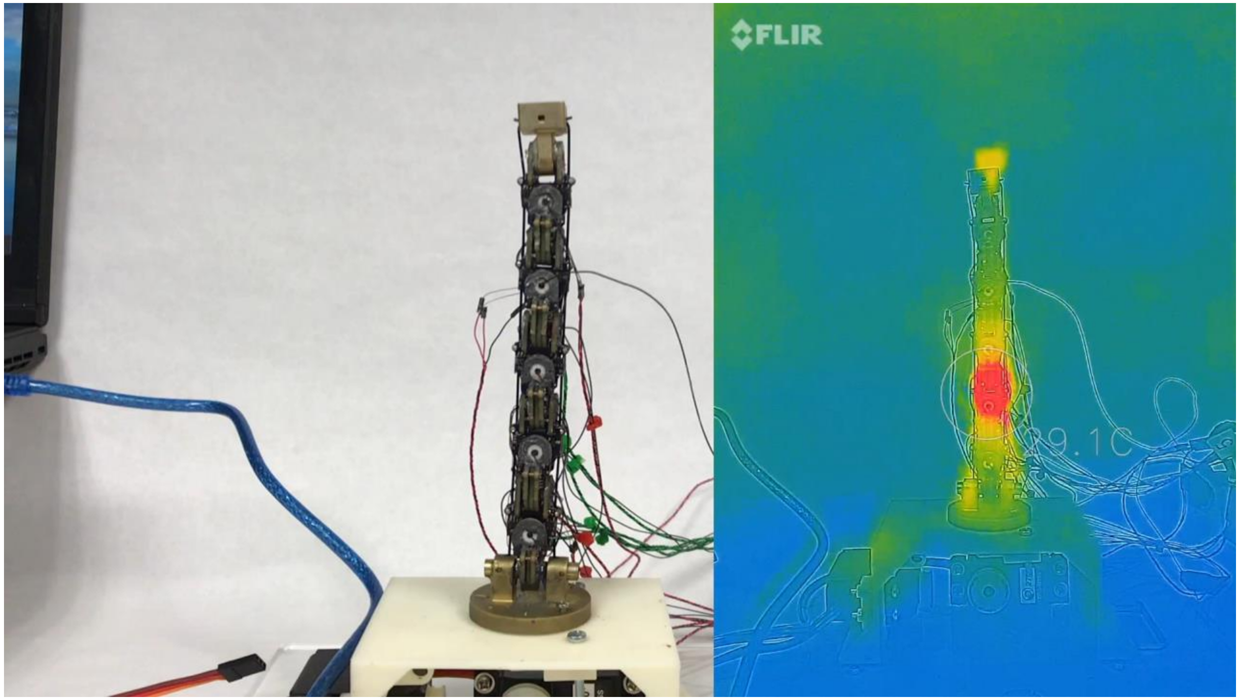
New Hyper-Redundant PCB-Based Robot



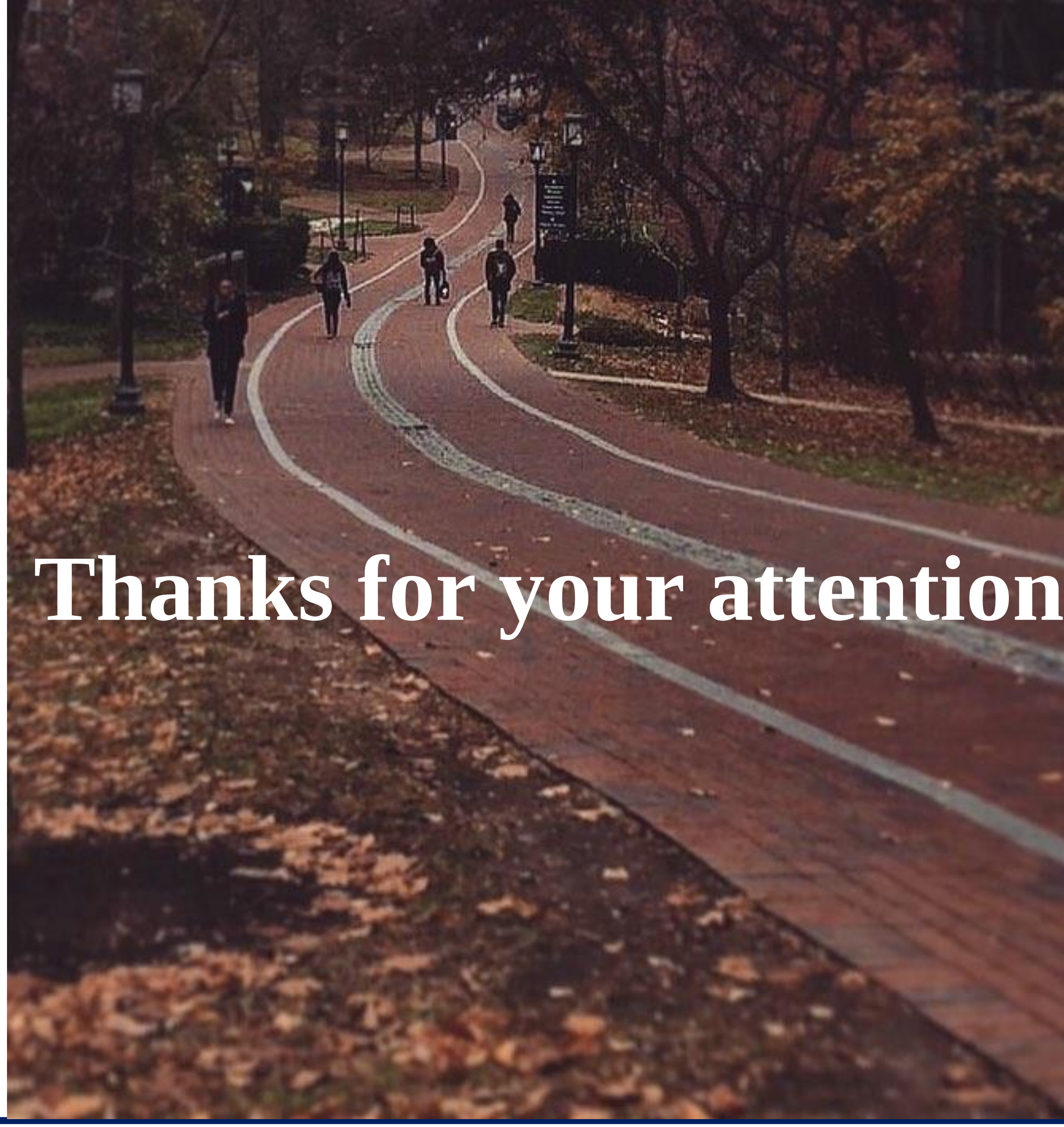


Slide is courtesy of Alex Cohen.

Concluding Remarks

- **Dexterity** and **Flexible Access Surgery** is a Crucial need in Orthopedics.
- Novel Continuum Manipulators, cutting Tool and Sensing units need to be designed to address the mentioned need.
- Robots and Surgeons can Synergically work together to improve autonomy in Medical Robotics.
- Novel Perception and Learning algorithms are needed to ensure safety during the procedure.

- **Variable stiffness** robots can address the limitation of current CMs working on both soft and rigid tissue.



Thanks for your attention

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