Continuum Tube Robot for Infrastructure Inspection

Friday, February 9, 2024

Sponsor: **Asst. Prof. Kefei Wen**

UBC Mechanical Engineering Department,

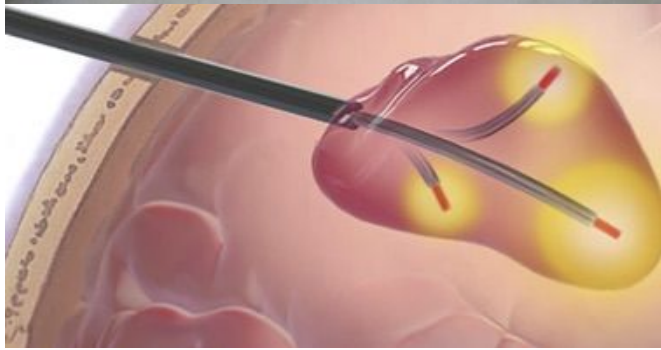
Principal Investigator, UBC Advanced Robotics Lab.

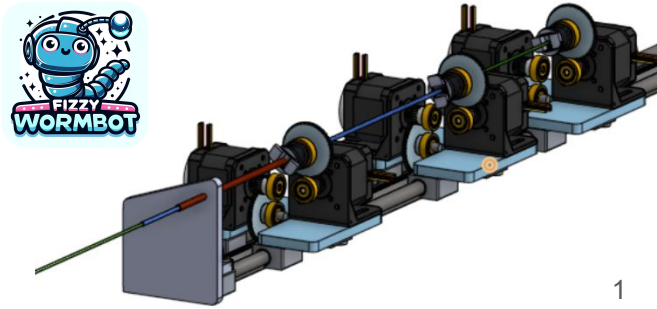
Mark P.

Cindy Z.

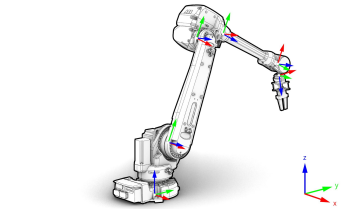
Joseph K.

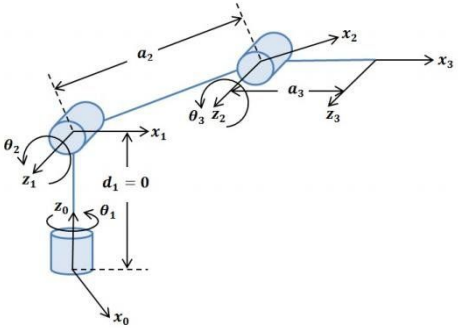
Tyler W.





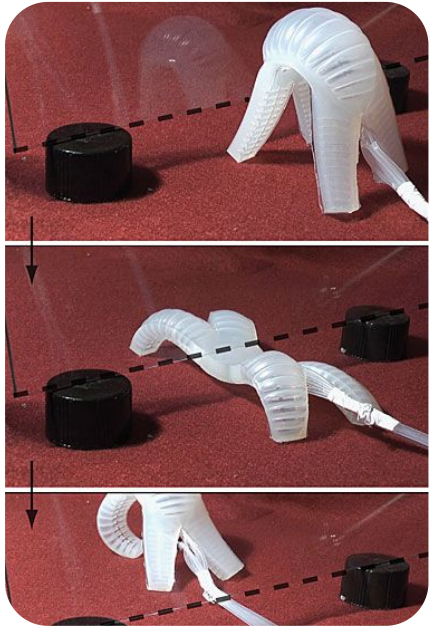
“Robot”, what do you imagine?

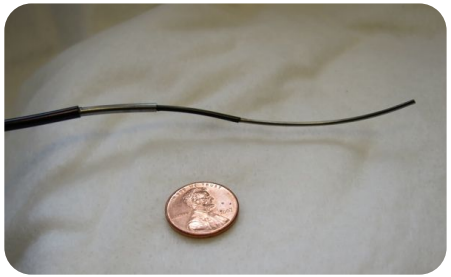




What if robots are “soft” and compliant?

Rigid Robotics

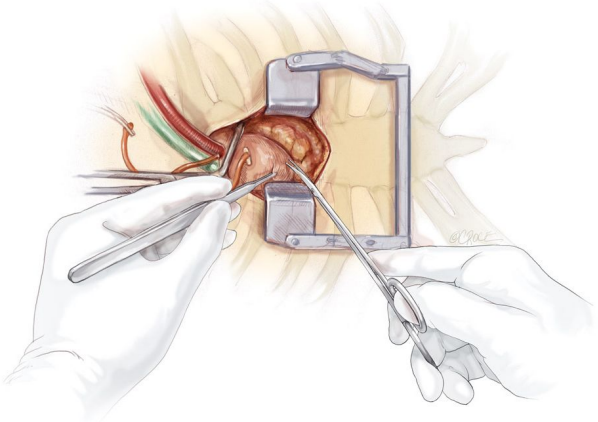


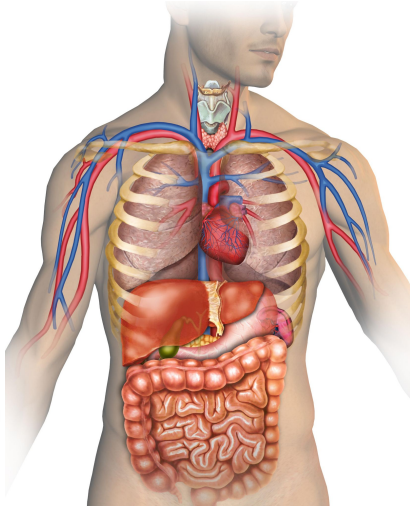


Harvard Soft Robotics Lab

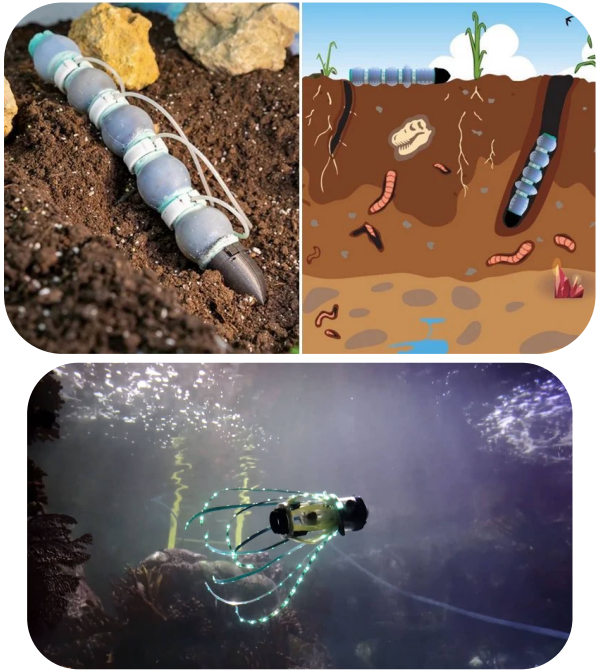
Soft Robotics

What are soft robots useful for?





Navigate complex anatomy with minimal contact?



Unstructured, foreign environment

A Look at Continuum Tube Robots

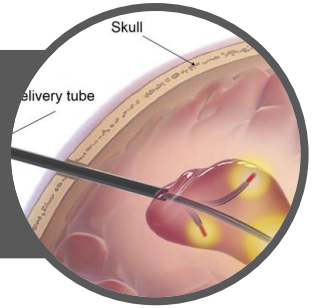
Paper

GitHub

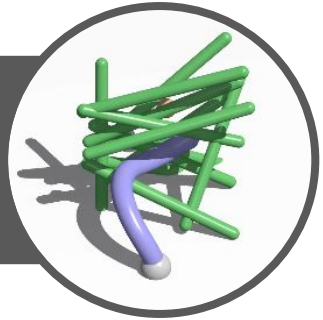
UNIVERSITY OF TORONTO Robotics Institute

NSERC CRSNG

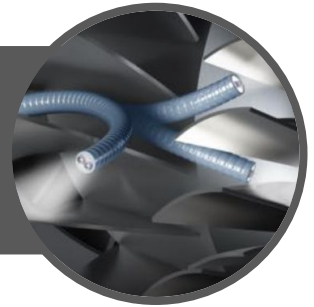
Minimally Invasive Surgery



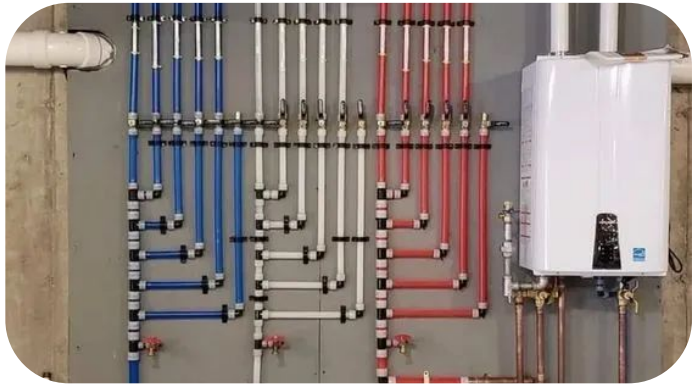
Search & Rescue

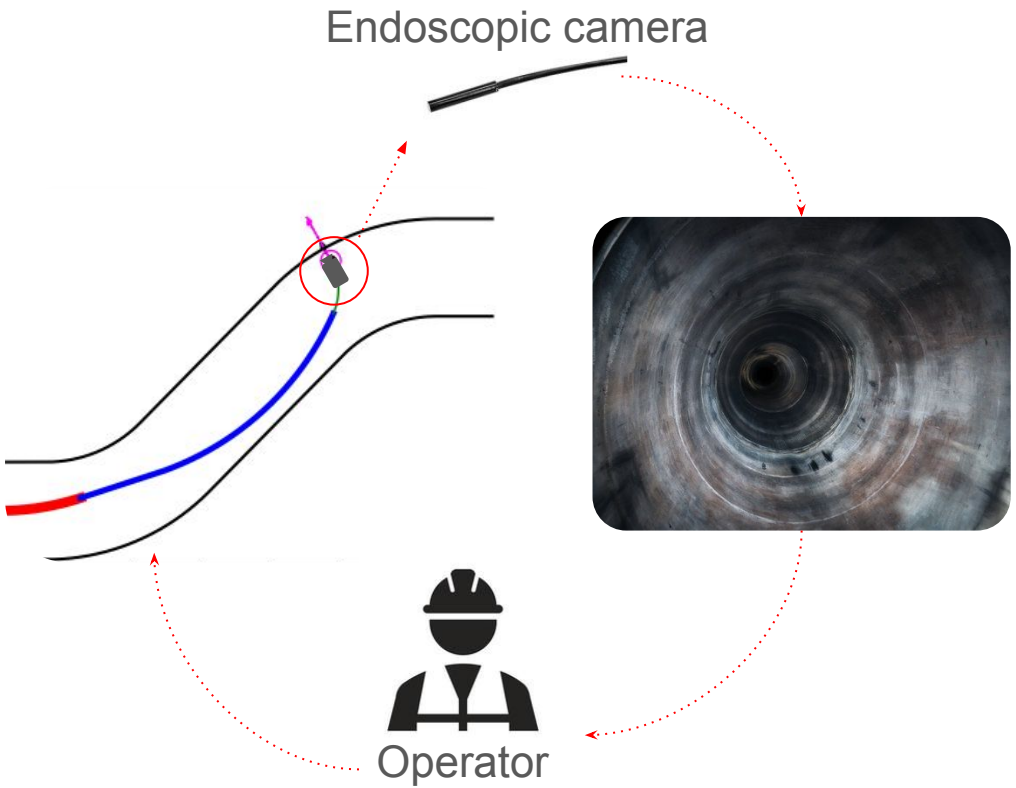


Exploration & Inspection

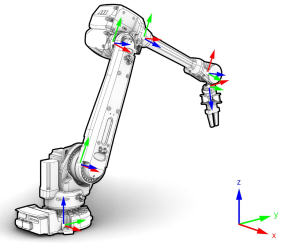


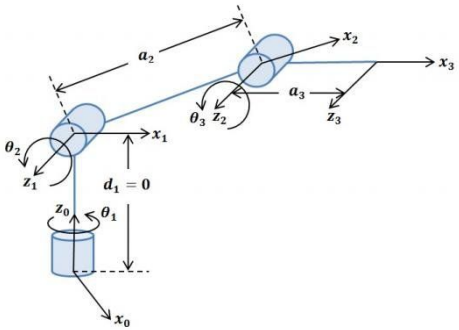
Continuum Tube Robot for Pipe Inspection

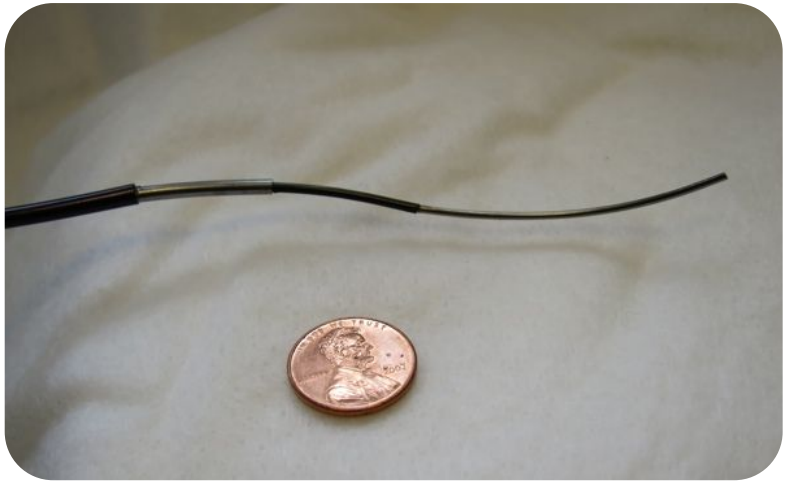




Modelling of a continuum robot is challenging!



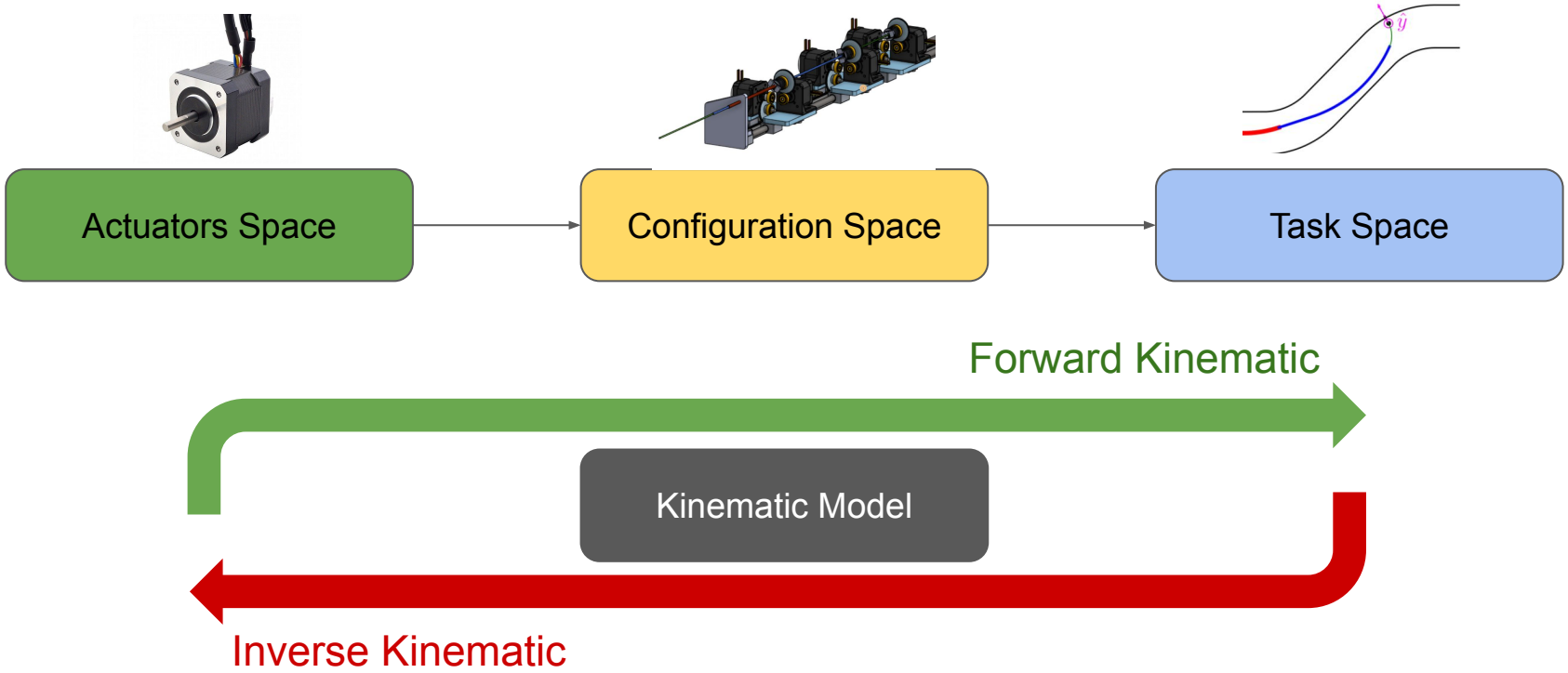




Rigid robots: finite joints
(Often) Assume rigidity

Continuum robots: *infinitely many* joints
Deflection creates motion

Modelling of a continuum robot is challenging!



Modelling of a continuum robot is challenging!

Physics-based

Data-based

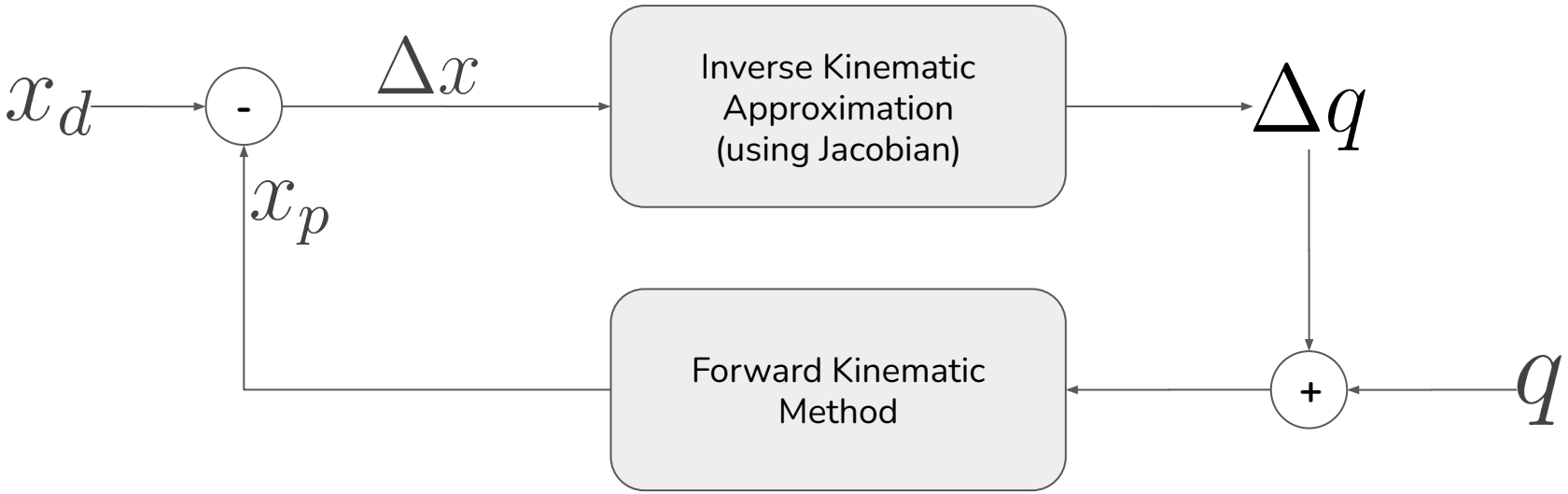
		Dominating Stiffness	Constant Curvature	Cosserat Rod Theorem	Supervised Learning / RL
Include?	**Bending**				N/A
	Torsion				N/A
Error (% of total length)		> 3%	3%	**1%**	< 1%
Implement Difficulty		Easy	Intermediate	Hard	???
		(Done!)	**Year 1**	**Year 2**	

Overview of Software Control

x_d = **Desired position and angle**

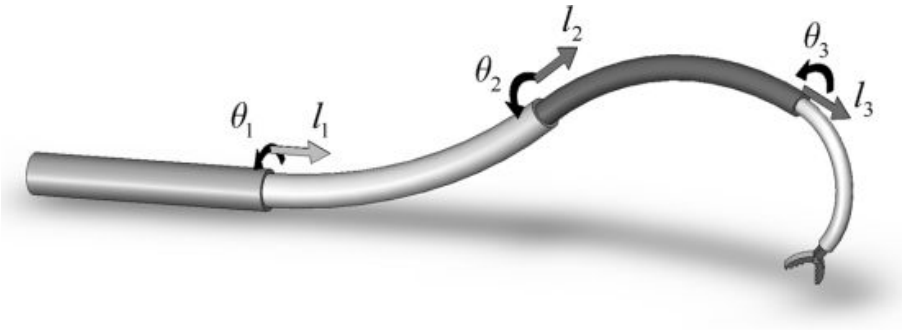
x_p = **Predicted position and angle**

q = **Motor inputs**



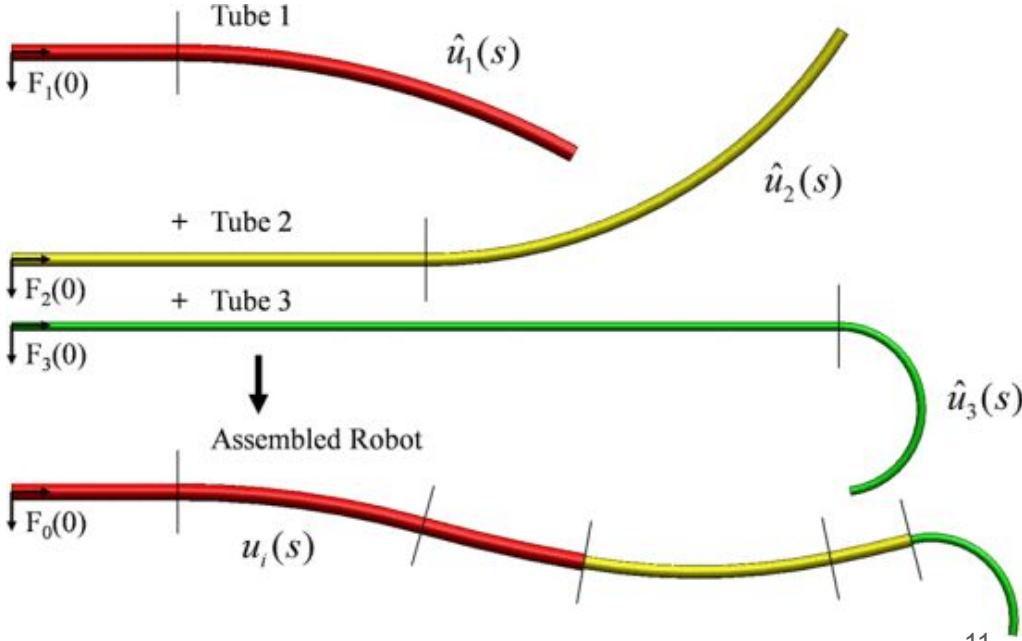
Tubes

Overview



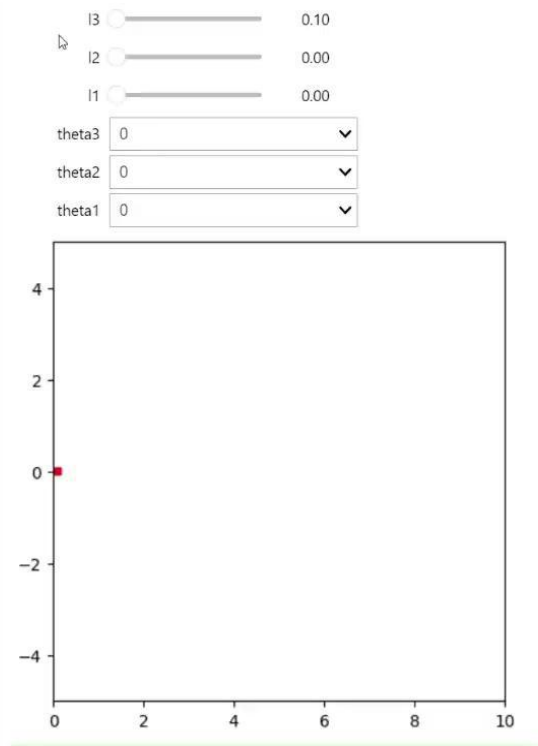
Initial design decisions:

- Total extension to be approximately 20cm
- Using 3 tubes to provide 6 degrees of freedom
- All tubes will be made of the same material
- Tubes will be of piecewise-constant curvature
- Stiffness of outer tubes dominates inner tubes

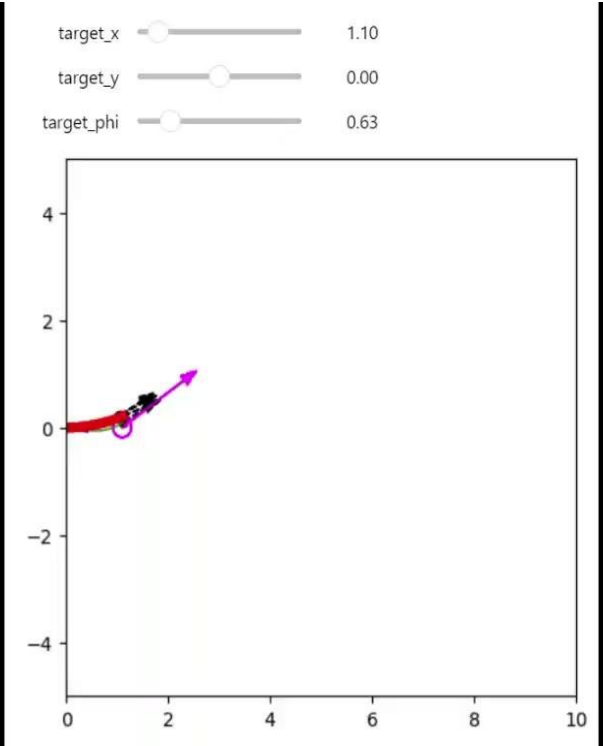


Kinematic Model: Dominating Stiffness

Forward Kinematic



Inverse Kinematic

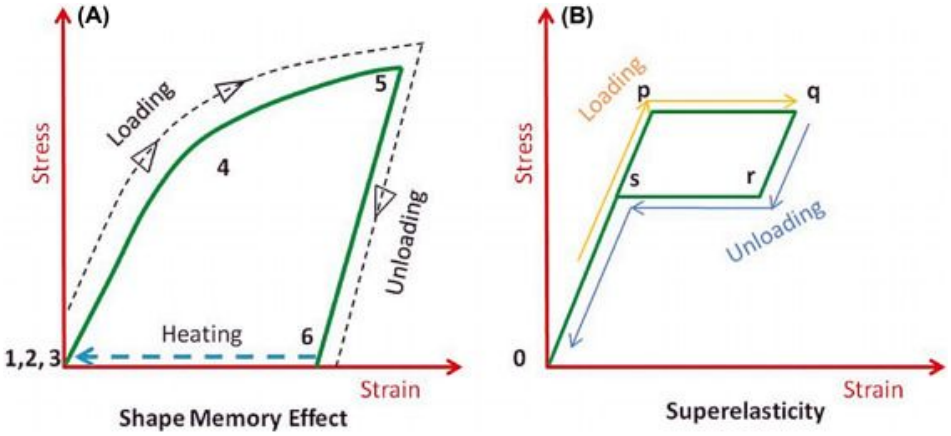


Tubes

Material

Industry standard is nitinol tubes. They have the following properties:

- Superelastic
- Biocompatible
- More durable than other superelastic materials

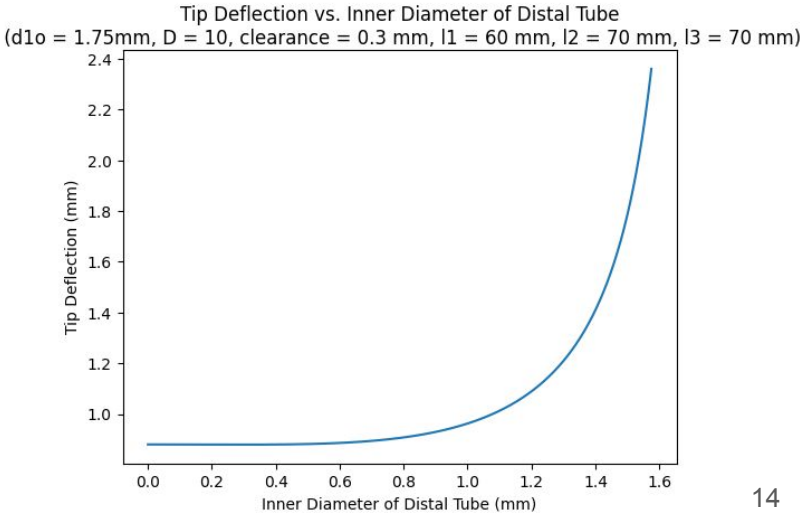


Tubes

Diameters

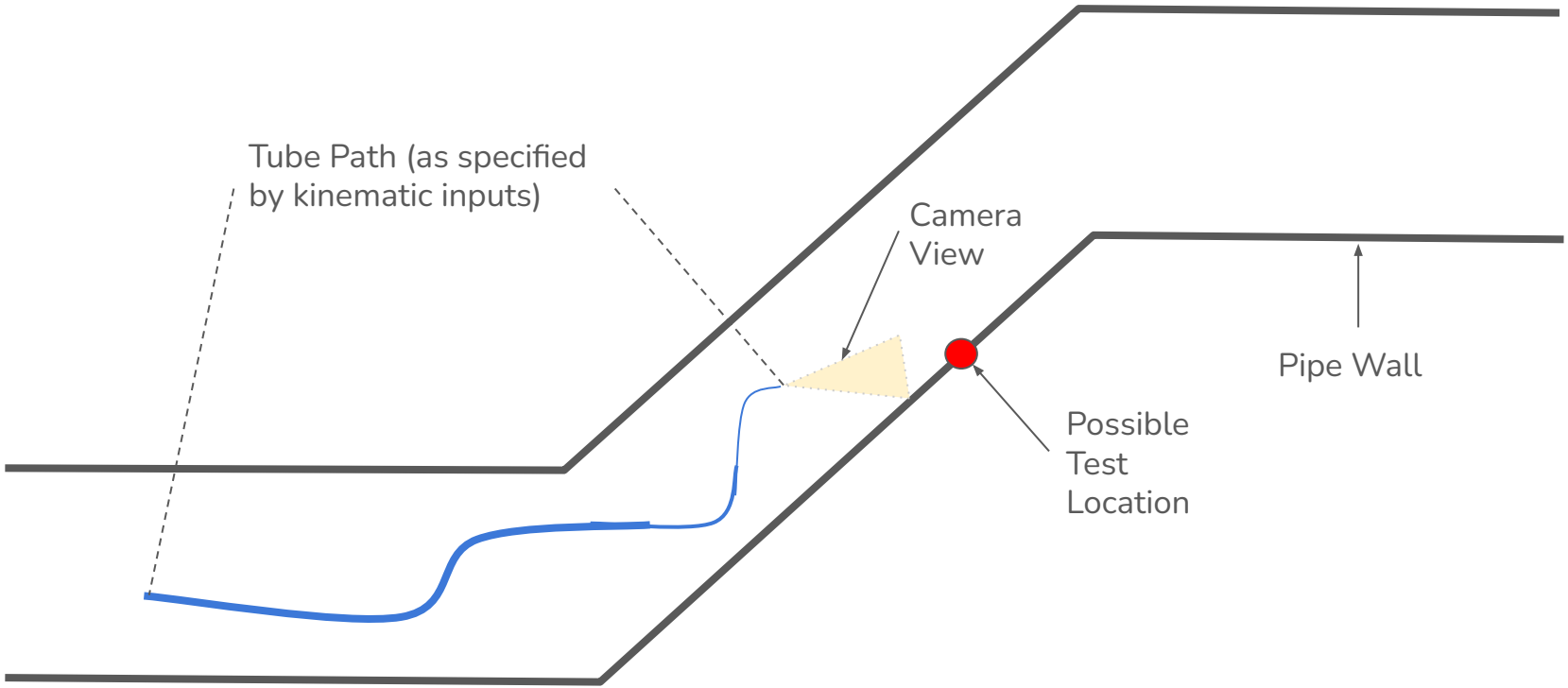
To choose the diameters, we made the following considerations:

- Large stiffness ratio between concentric tubes for compliance
- Tube clearances to minimize friction
- Maximum estimated tip deflection < 1%
- Distal tube diameter large enough to support camera



Tube Parameters Optimization

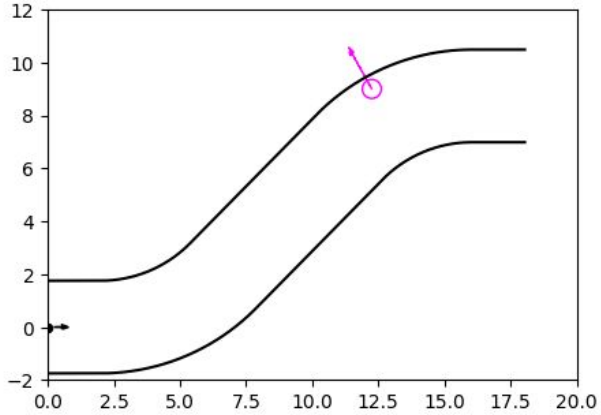
Workspace setup

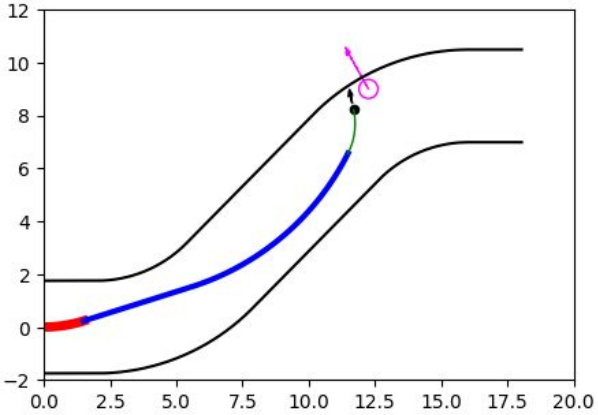


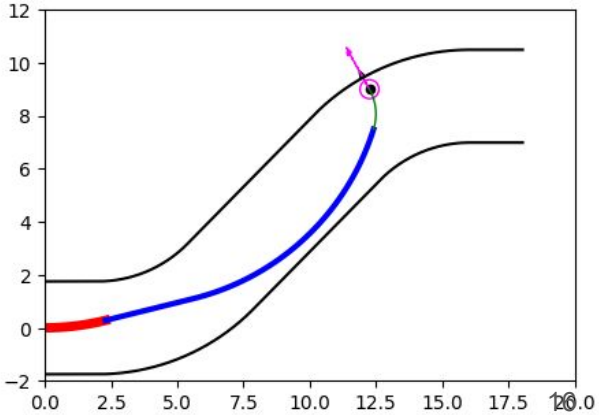
Tube Parameters Optimization

Optimization Process

Test Location → Inverse Kinematic Model → Tube Parameter Optimization

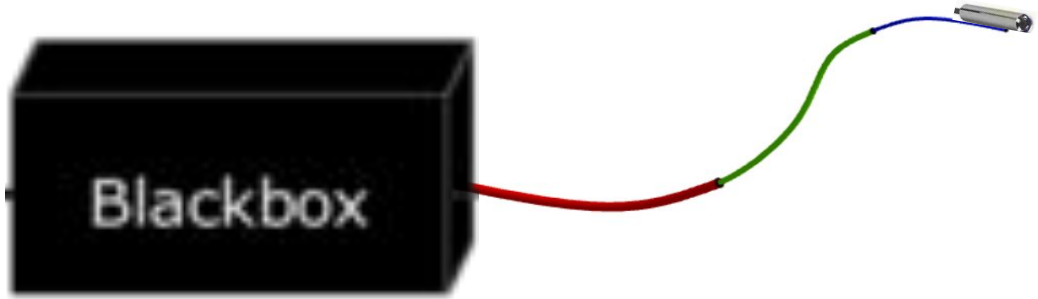






Hardware

1. How do we move the tubes to achieve 6 DOF control of robot tip?



Grassman et al., 2023

Hardware

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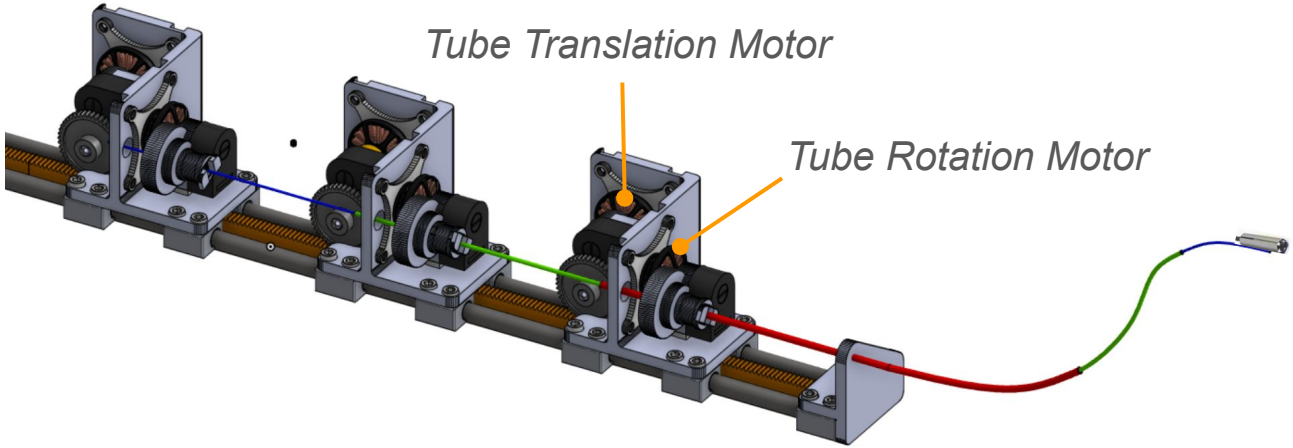
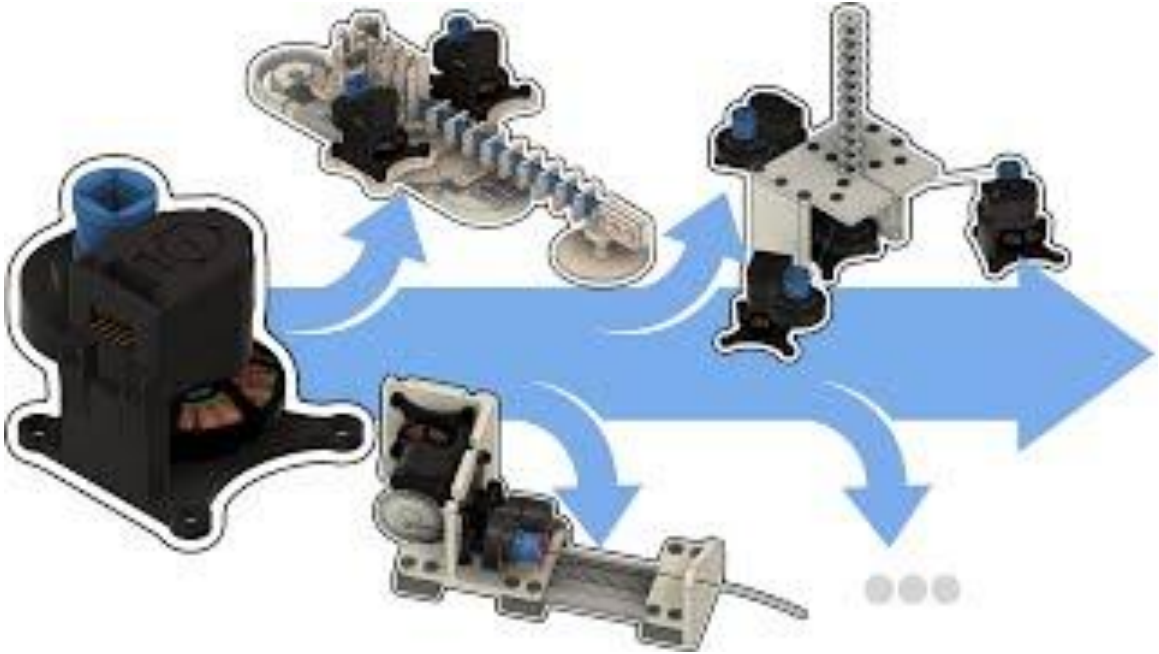


Grassman et al., 2023

Hardware

2. U of T’s design (which we have adapted and modified) in action:

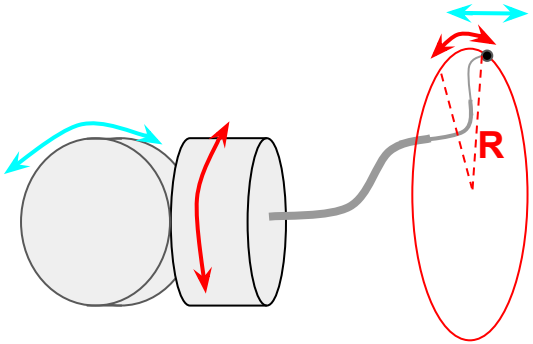


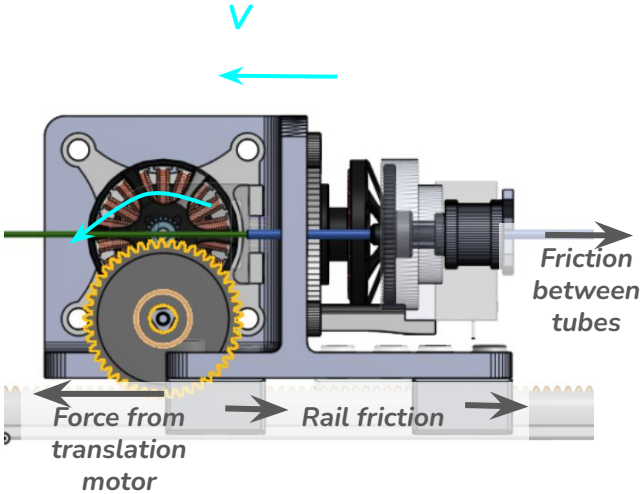
(Grassmann et al, 2023) Note: our design has three actuation units, not two, for six DOF

Hardware

3. Motor precision and torque requirements

We needed a more affordable alternative to U of T's BLDC motors and drivers, so we first determined motor specs:





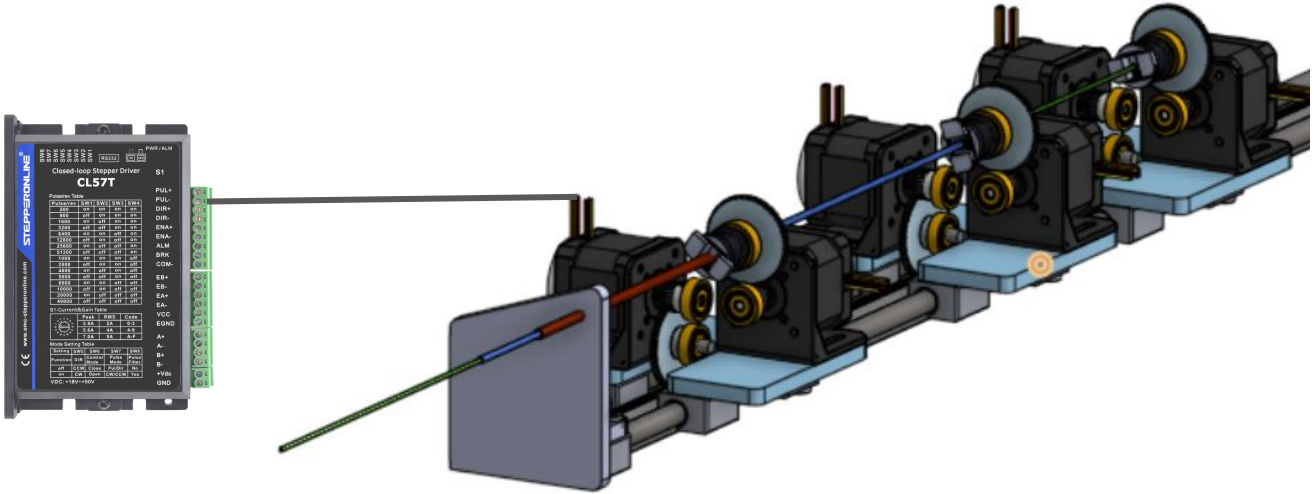
Step size <0.5% of max tubes length (20cm)

Module mass x acceleration =
Force from translation motor - total friction

Hardware

4. Stepper Motor

We identified these Nema 17 closed-loop stepper motors (17HS15-1504-ME1K), run at eight microsteps per step, as an affordable alternative:

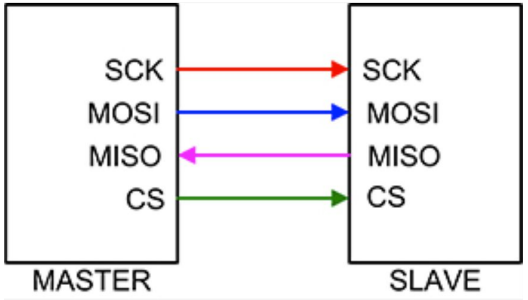


BLDCs+Drivers Cost = $1700 CAD v.s. Steppers+Drivers Cost = $468 CAD

Electrical Control System

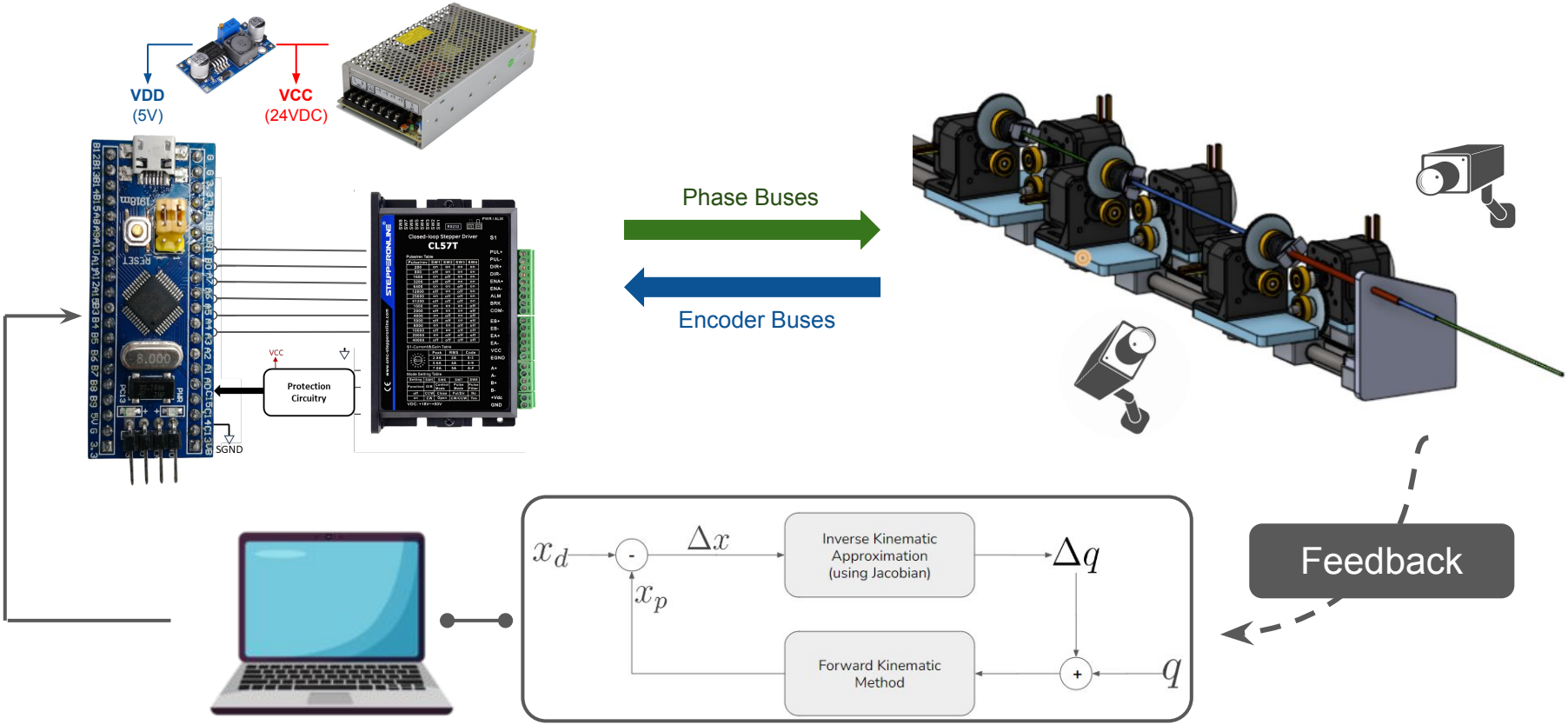
Communication Protocol: SPI

- MCU selected is the Blue Pill
- Many microcontrollers have built in SPI peripherals
- Low latency communication
- Good for short distances
- Can accommodate for multiple devices
- Requires USB to SPI adapter to interface with PC



Control Signals

System Overview

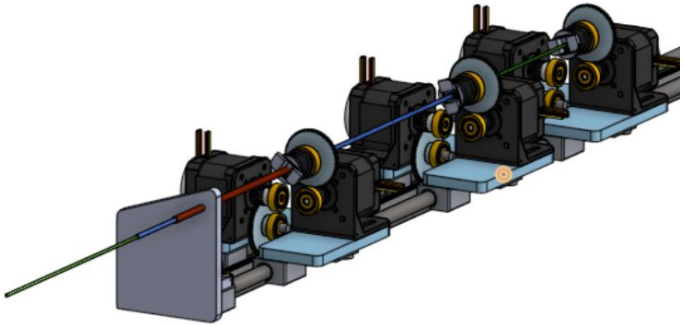


Project's Milestones

Year 1

CTR Design & Construction

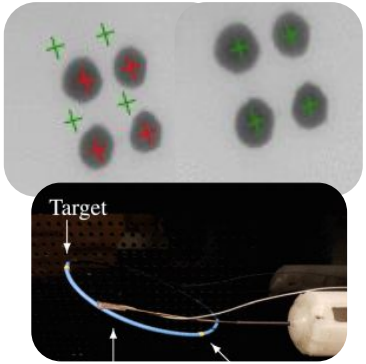
Basic Open-loop control

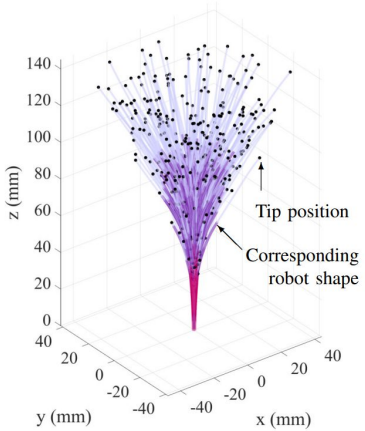


Year 2

Teleoperation

ML for autonomous
Closed-loop control





Challenges of Project

CHALLENGE: NITINOL TUBES

- Very few suppliers for Nitinol Tubes
- No quote or pricing estimate
- Estimated long manufacturing time
- Custom pre-curving services is still unknown
- Main concern is the unknown cost

POSSIBLE SOLUTIONS

- Purchasing straight tubes and curving them ourselves to lower cost and manufacturing time
- 3D printed tubes as a proof of concept

Action Items Going Forward

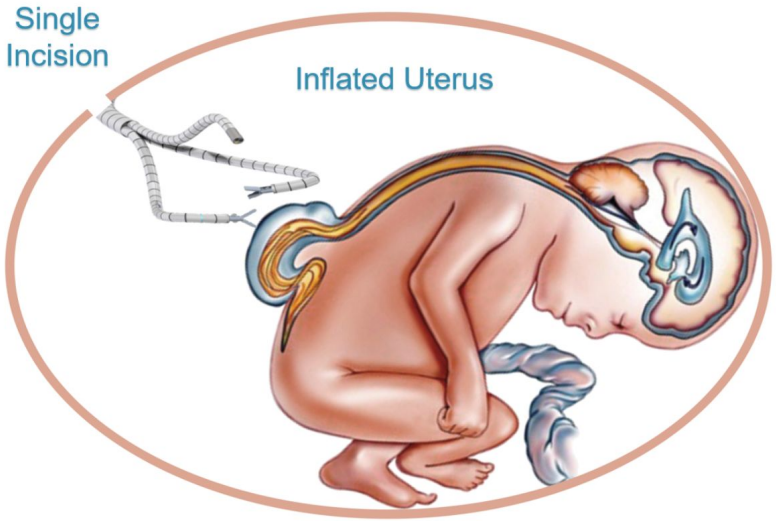
		TARGET DEADLINE
MECHANICAL	Finalize CAD model and component selection to start mechanical prototype	Prototype by End of Feb/Early March
ELECTRICAL	Create benchtop setup using motors, drivers, and MCU	Setup by End of Feb/Early March
SOFTWARE	Begin implementing proposed algorithm in code and enabling communication between PC and MCU	End of Feb/Early March

Project Prospects

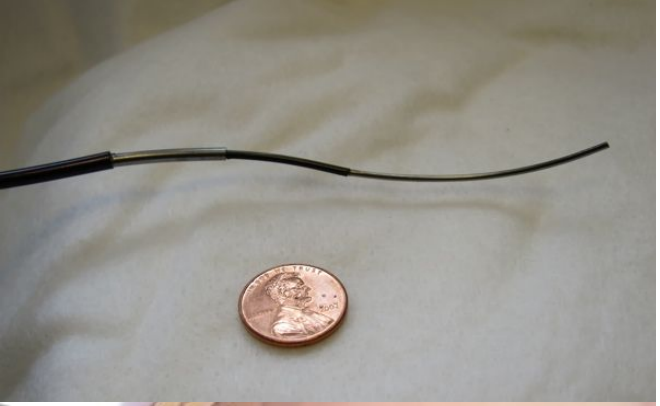
Pipe Inspection while mounted on robotic dog

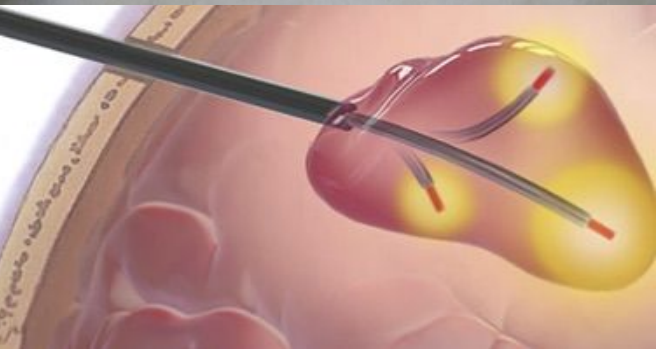
Boston Dynamics

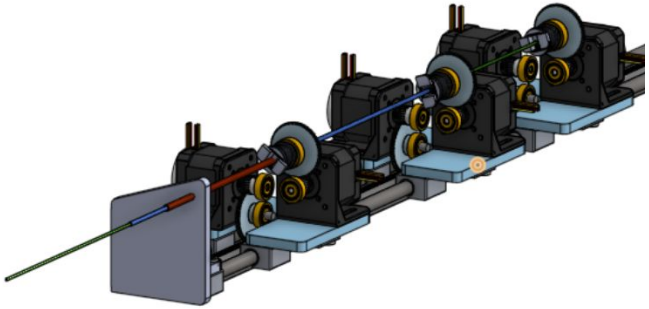
CTR used in surgical purposes to reduce lesions and risk of infections



(Poortan et al, 2023)







Continuum Tube Robot for Infrastructure Inspection

Friday, February 9, 2024

Sponsor: **Asst. Prof. Kefei Wen**

Thank You! Q&A

Mark P.

Cindy Z.

Joseph K.

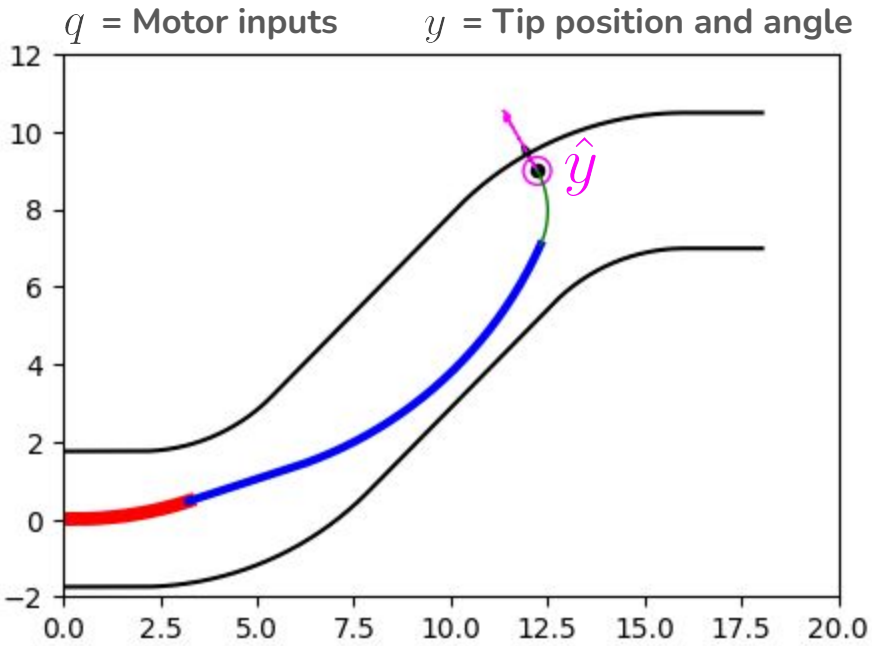
Tyler W.

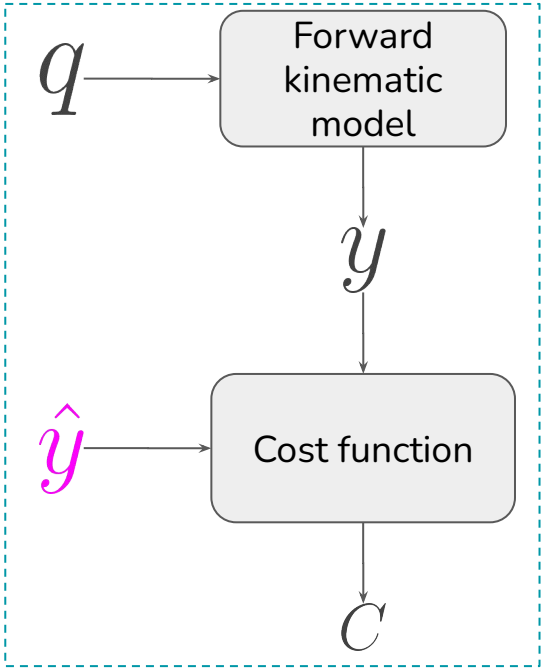
Image Credits

[1] Top:
Middle:
Bottom:
[2] Left: MIT Review, Boston Dynamics’ dog robot Spot is going to patrol an oil rig in Norway
Middle: TechCrunch, Sanctuary AI’s new humanoid robot stands 5’7″ and lifts 55 lb
Right-Top:
Right-Bottom:

Appendix

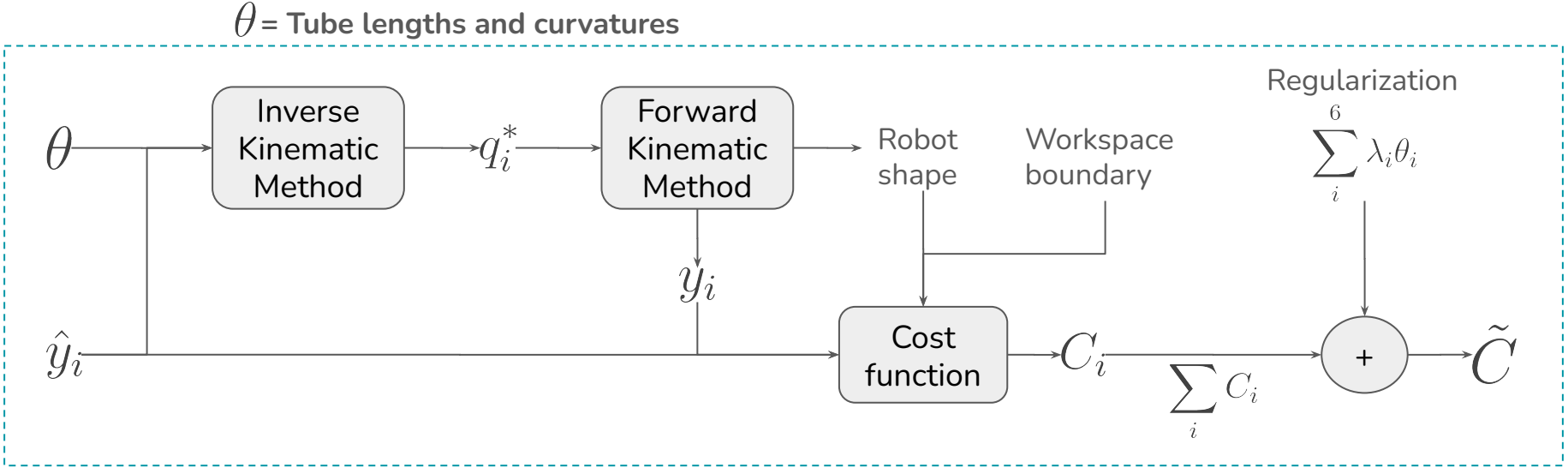
Inverse Kinematic Method





$$q^* = \underset{q}{\operatorname{argmin}}\,(C)$$

Tubes Parameter Optimization



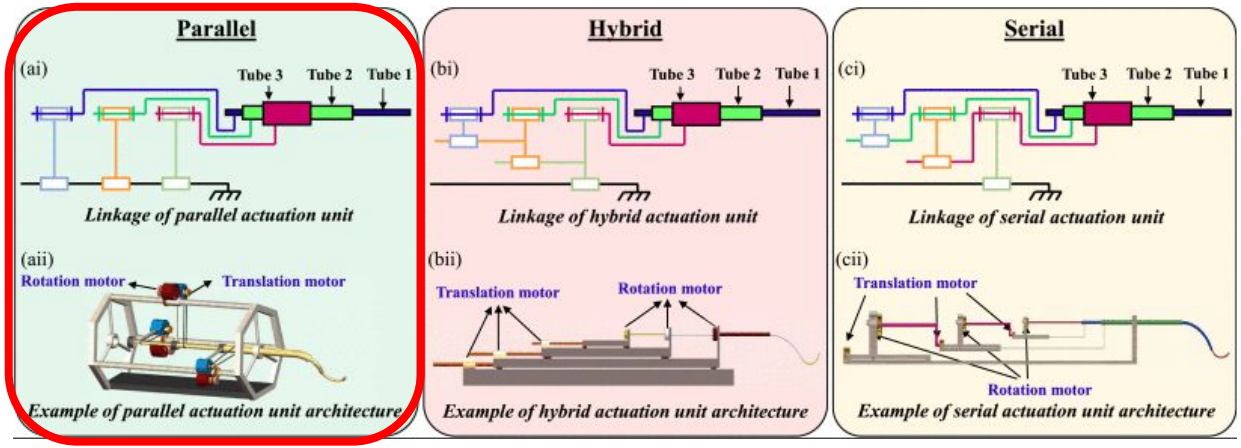
$$\theta^* = \underset{\theta}{\operatorname{argmin}} \left(\tilde{C}\right)$$

Hardware

Parallel architecture chosen for modularity

Parallel:

- Modular
- No coupling of DOF
- No error accumulation
- One drawback: less range



Nwafor et al., 2023

Endoscopic Camera

2. Selection

Vividia FC-4010

∅ 4mm

$276 CAD

Voltcraft 516947-BP

∅ 5.5mm

$489 CAD

Tolos OVM 9734

∅ 3.9mm

$120 CAD

Endoscopy Camera

2. Selection

Diameter			
Rigid Section Length			
Cost (CAD)			
IP67			
Resolution			

Bill of Materials

Item	Part Number	Website to Order from	Price (CAD)	Quantity	Shipping Time	Total Price
BLDC Motor	T-Motor MN4004	T-Motor or Aliexpress	~$203 for 2 motors ($145.80 USD)	8	10-15 working days + free shipping	**$800**
Encoder	Avago AEDM-5810	Digikey	$93.90	9	1 day + free shipping	**$837.81**

Total pricing for only encoders + motors: **~$1637.81**

*not including taxes and note we only need 6 of each for the design itself so this would give us 2-3 extra parts of each component

Bill of Materials

Item	Part Number	Website to Order from	Price (CAD)	Quantity	Shipping Time	Total Price
Gear Motor	2662N313	McMaster-Carr	$10.00 ($7.34 USD)	9	1-2 days	**$90.00**
Gear Encoder	2662N321	McMaster-Carr	$15 ($10.66 USD)	9	1-2 days	**$135.00**
Ball Bearing	5972K91	McMaster-Carr	$6.60 ($4.82 USD)	18	1-2 days	**$118.80**
Screw M3x10	91290A115	McMaster-Carr	$13.00 per pack of 100 ($9.54 USD)	18	1-2 days	**$13.00**
Nut M3	90593A001	McMaster-Carr	$15.50 per pack of 100 ($11.38 USD)	18	1-2 days	**$15.50**

Bill of Materials

Item	Part Number	Website to Order from	Price (CAD)	Quantity	Shipping Time	Total Price
Rail	WS-10-40	Igus	$98 per 1m ($71.82 USD)	1m	1-5 days (only ships to US)	**$98.00**
Pillow Block	WJ200UM-01-10-AL	Igus	$23 ($16.65 USD)	22	1-5 days (only ships to US)	**$506**
Gear Rack	2662N57	McMaster-Carr	$8.20 ($5.90 USD)	5	1-2 days	**$41.00**
Gear	2662N42	McMaster-Carr	$13.62 per pack of 100 ($10.03 USD)	5	1-2 days	**$68.10**
M16x14 Screw	91290A319	McMaster-Carr	$25.75 per pack of 100 ($18.93 USD)	90	1-2 days	**$25.75**

Continuation of BOM

Item	Part Number	Website to Order from	Price (CAD)	Quantity	Shipping Time	Total Price
M6 Nut	90593A005	McMaster-Carr	$16.30 per pack of 50 ($11.55 USD)	36	1-2 days	**$16.30**
BLDC Driver	BOOSTXL-DRV8305EVM	Digikey	$145.58	8	1 day + free shipping	**$1164.64**
Evaluation Board w/ Microcontroller	LAUNCHXL-F28069M	Digikey	$67.42	5	1 day + free shipping	**$337.10**
Camera	N/A	Alibaba	$218.39 for 2	2	Shipped	**$218.39**
Tubes	N/A	Euroflex	TBD	3	TBD	**TBD**

Summary of Budget

- Current Budget allocated: **$3500**
  - $2000 from sponsor, $1500 through PLab

- Total pricing for all: **~$4485.39**
  - includes > part quantity than needed for design
  - not including taxes, cost of tubes, shipping or 3D printed parts

Side note: UofT design cites their design (only 2 actuation units) costing ~$1750 USD or ~$2450 CAD