ME 531 Final Project: Vine Robot Control

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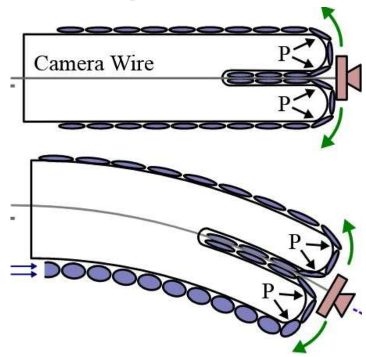
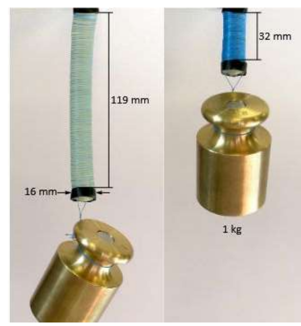
ME 531

Introduction

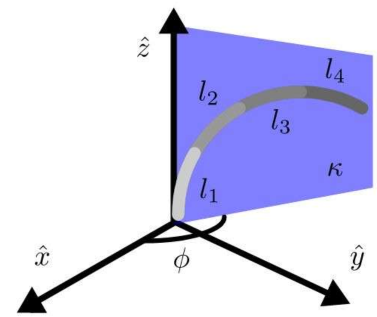
- Vine robots are a kind of soft robot that locomote by growing
  - Made of inflexible soft plastics
  - Can be actuated by pneumatic artificial muscles
- Vine robots can be useful for exploration, inspection, etc
- Because of their compliance, bespoke hardware, and difficulty with proprioception controlling vine robots is still an open research question



Vine robot steering [1]



IPAM Contraction



Constant curvature model [1]

Choosing a Model

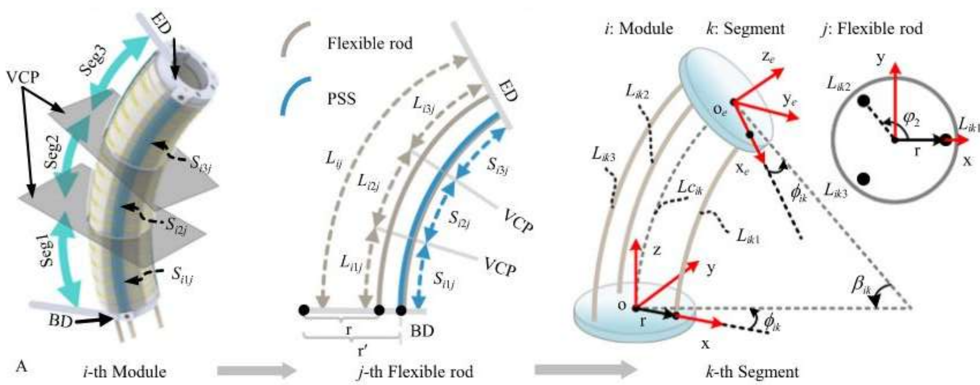
➢ A paper from Cecilia Laschi's group implements closed loop control for a continuum robot with multiple sections [1].

- They develop a kinematic model for a robot controlled by changing edge length
- Desired change in actuator length (ΔL) is then calculated using least-square optimization

$$\underset{\Delta \boldsymbol{L}}{\arg\min} \; \left\| \mathbf{J}\Delta \boldsymbol{L} - K_p \boldsymbol{e} \right\|^2 + \lambda^2 \left\| \Delta \boldsymbol{L} \right\|^2 \qquad \underset{\Delta \boldsymbol{L}}{\arg\min} \; \left\| \mathbf{J}\Delta \boldsymbol{L} - K_p \boldsymbol{e} \right\|^2 + \lambda^2 \left\| \Delta \boldsymbol{L} \right\|^2$$

- J is the Jacobian, e is the error in the tip pose, Kp and λ are tunable constants

➢ This paper does not implement any dynamic modeling



$$\boldsymbol{R}_k^{k-1} = \mathrm{Rot}(\mathbf{Z}_{k-1}, \phi_k)\,\mathrm{Rot}(\mathbf{Y}_{k-1}, \beta_k)\,\mathrm{Rot}(\mathbf{Z}_k, -\phi_k)$$
$$= \begin{bmatrix} \cos\beta_k(\cos\phi_k)^2 + (\sin\phi_k)^2 & (-1+\cos\beta_k)\cos\phi_k\sin\phi_k & \cos\phi_k\sin\beta_k \\ (-1+\cos\beta_k)\cos\phi_k\sin\phi_k & (\cos\phi_k)^2 + \cos\beta_k(\sin\phi_k)^2 & \sin\phi_k\sin\beta_k \\ -\cos\phi_k\sin\beta_k & -\sin\beta_k\sin\phi_k & \cos\beta_k \end{bmatrix},$$

$$\boldsymbol{P}_k^{k-1} = \frac{1}{\rho_k}\left[(1-\cos\beta_k)\cos\phi_k \quad (1-\cos\beta_k)\sin\phi_k \quad \sin\beta_k\right]^{\mathrm{T}},$$

All images from [2]

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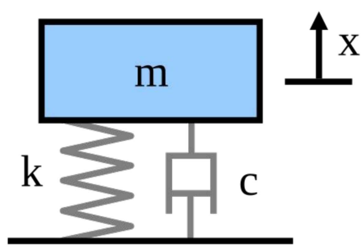
Implementing Dynamics

- There are numerous different methods for modeling the dynamics of continuum robots [3].
  - These methods are computationally heavy, complicated, and system dependent
  - We decided to use a more simple model that only considers actuator dynamics
  - We ignore effects of gravity and the internal pressure of the robot

- We model each actuator as a separate spring-mass-damper
  - This assumes each actuator acts like a spring with some mass and damping



- These actuators have no effect on eachother, but combined their lengths determine the overall shape of the robot

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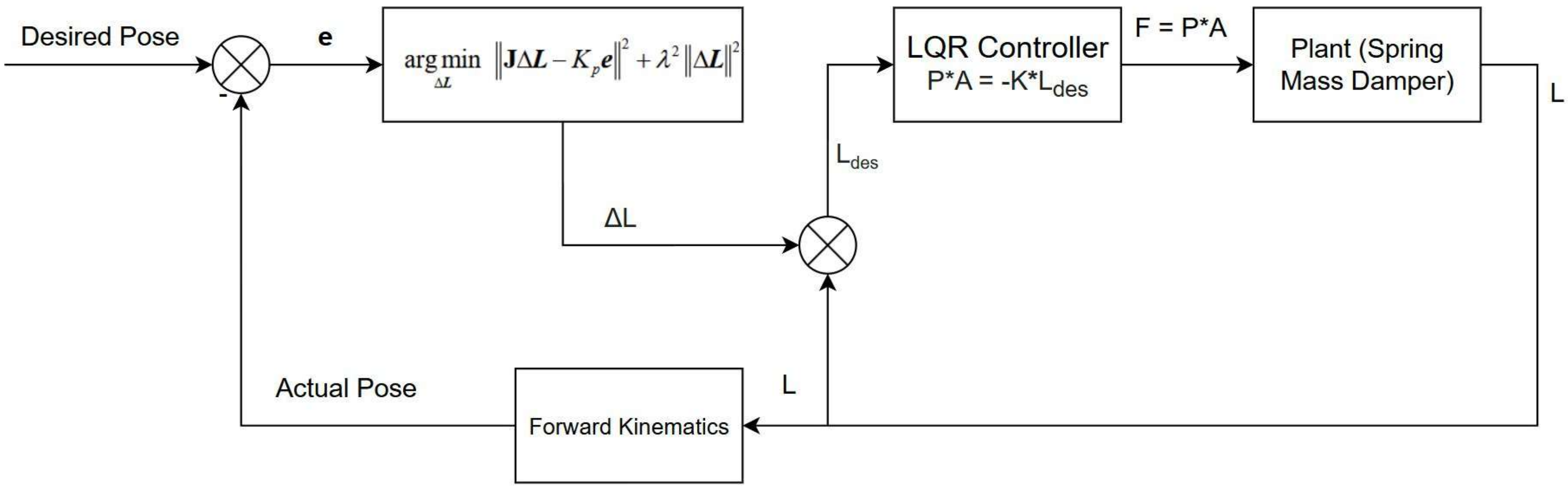
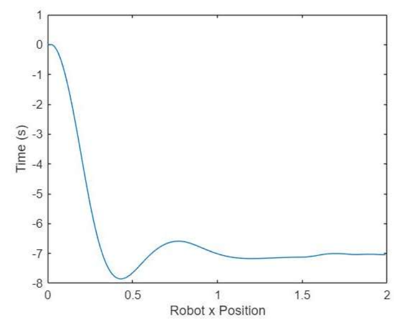
Block Diagram

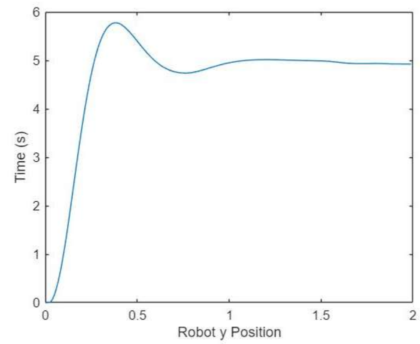


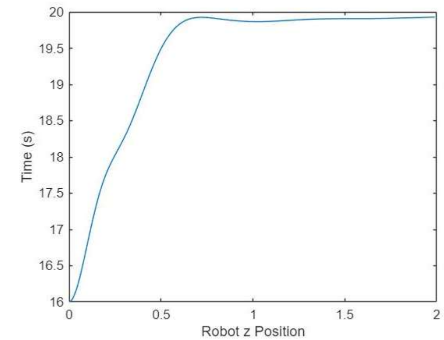
- The optimization part handles the nonlinear function mapping the desired pose to optimal changes in actuator length
- The LQR controller handles the linear actuator dynamics

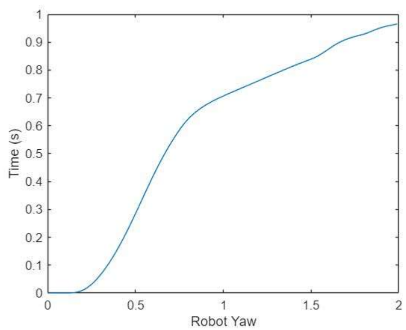
Results - 4 Segment Robot

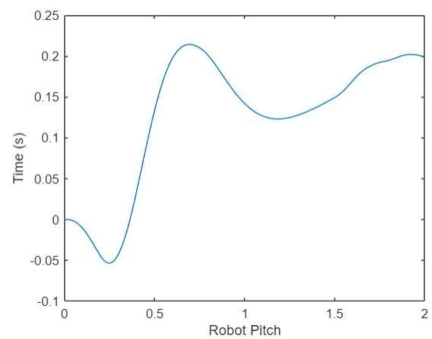
➢ The following graphs show the simulated robot pose over time
- Desired pose: [x=-7, y=5, z=20, yaw = 1.5, pitch = .1, roll = 1]

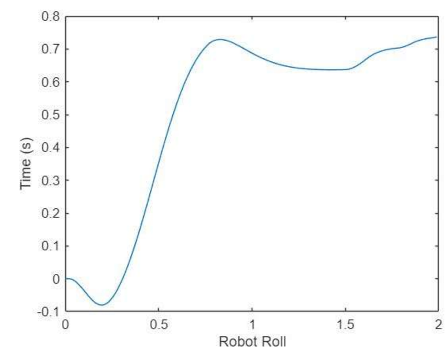




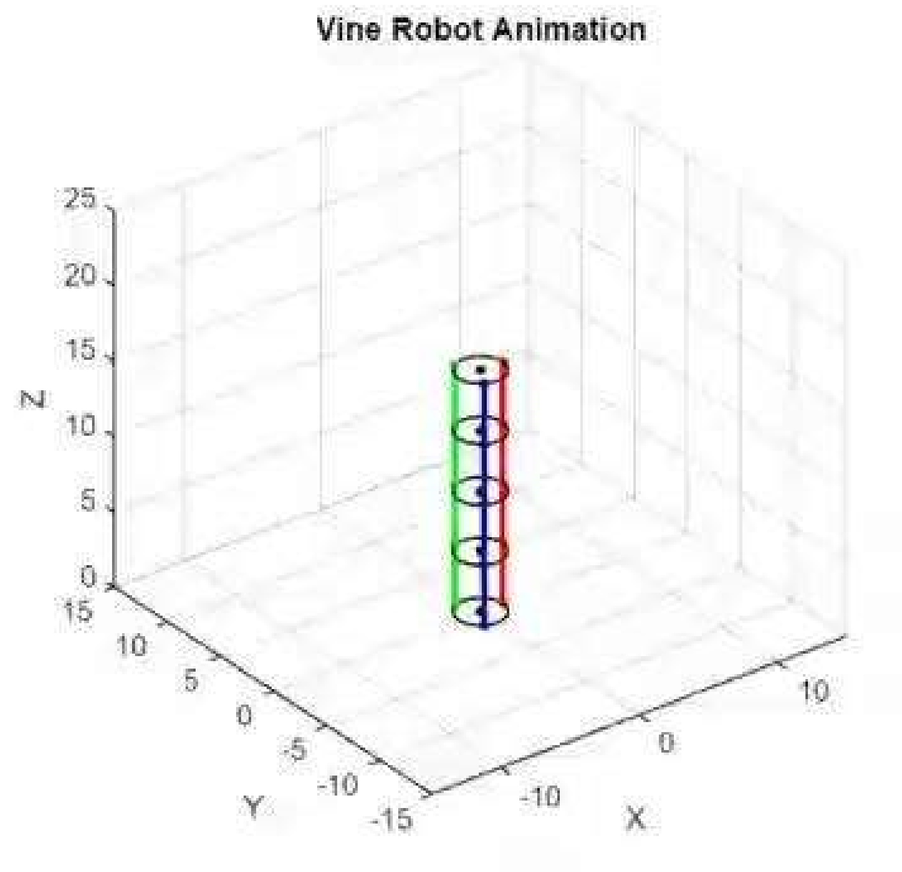






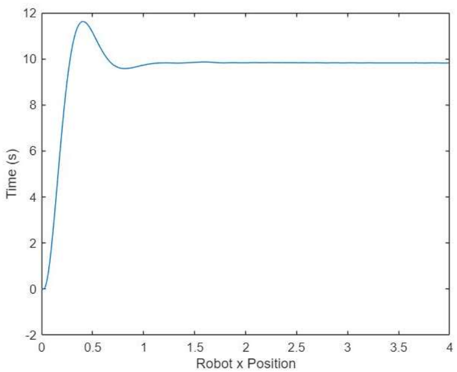


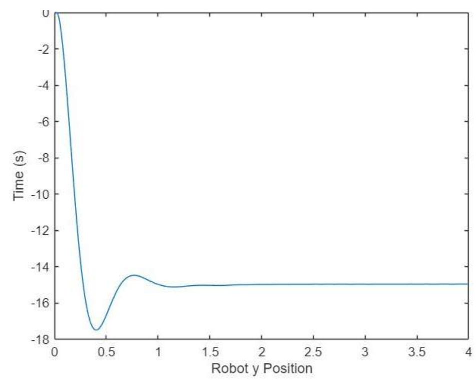
Video

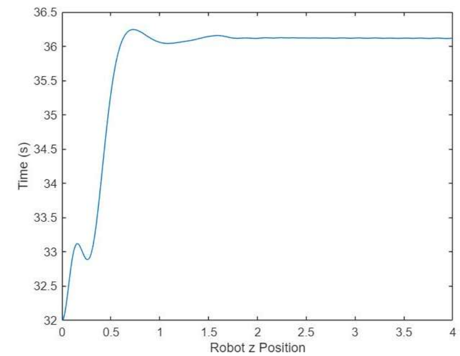


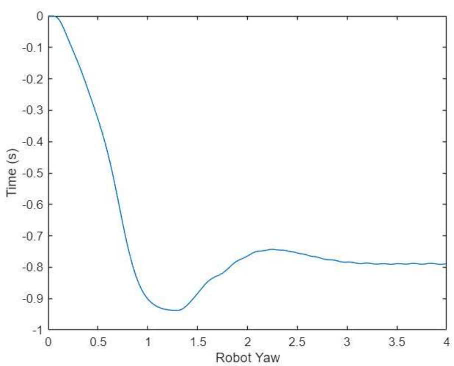
Results - 8 Segment Robot

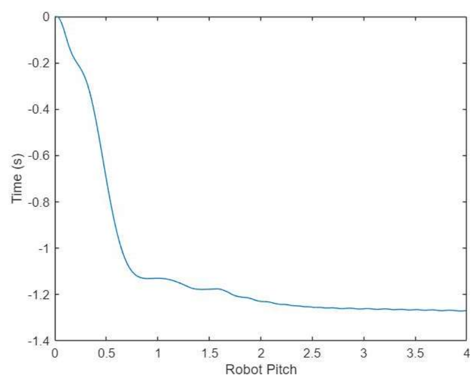
- Desired pose: [x=10, y=-15, z=36, yaw = -1, pitch = -1.5, roll = 0]

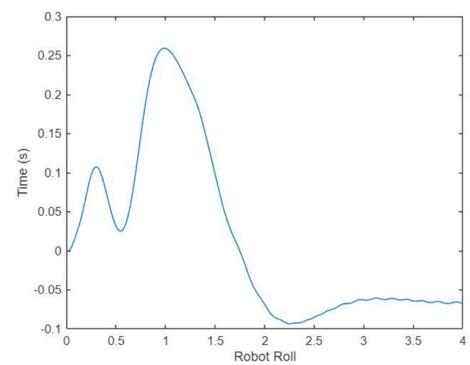




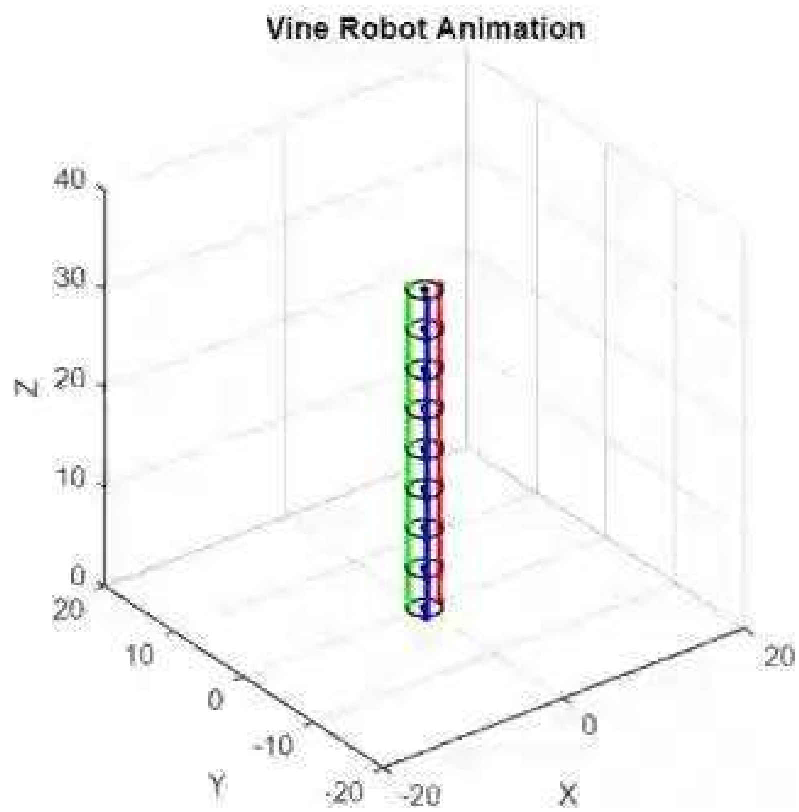








Video



Potential Future Work

- Hardware implementation

- Using a different deltaL calculator
  - Currently finds the minimum, which is not always ideal (limited actuator size)
  - This limits our range of possible poses

- Add an integrator for zero steady state error

- Designing a more robust dynamic model
  - Actuator interaction
  - Gravitational effects
  - Dynamics of the robot body and internal pressure

References

[1] Joseph D. Greer, Tania K. Morimoto, Allison M. Okamura, and Elliot W. Hawkes. “A Soft, Steerable Continuum Robot That Grows via Tip Extension”. Soft Robotics 2019 6:1, 95-108

[2] Wang, P., Xie, Z., Xin, W. *et al.* Sensing expectation enables simultaneous proprioception and contact detection in an intelligent soft continuum robot. *Nat Commun* 15, 9978 (2024). https://doi.org/10.1038/s41467-024-54327-6

[3] I. S. Godage, R. J. Webster and I. D. Walker, "Center-of-Gravity-Based Approach for Modeling Dynamics of Multisection Continuum Arms," in IEEE Transactions on Robotics, vol. 35, no. 5, pp. 1097-1108, Oct. 2019, doi: 10.1109/TRO.2019.2921153.

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