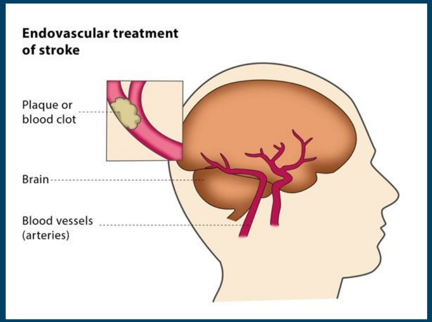
Control of VINE robot with Liquid Crystal Elastomer

By Alex Lu, Sarah Chang, Sukanya Krishna, Nicholas O'Shea, Yassin Fagelnour

Background

- There is a need for minimally invasive methods to reach aneurysms in the brain



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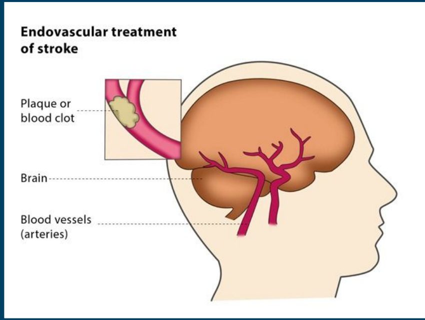
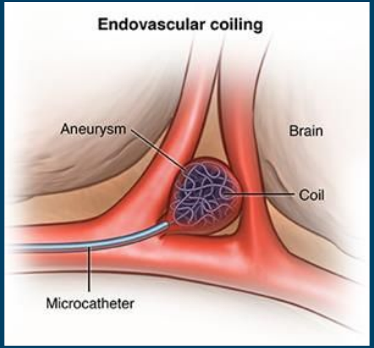
- Endovascular surgery is used to clear blood clots from inside the blood vessel (via catheterization)





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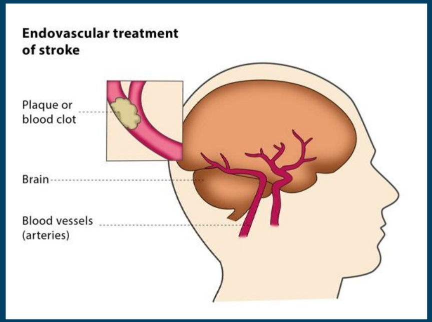

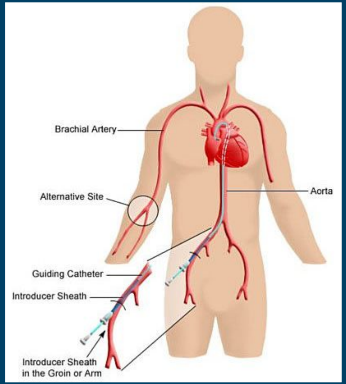

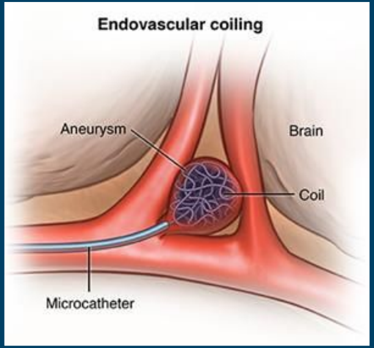

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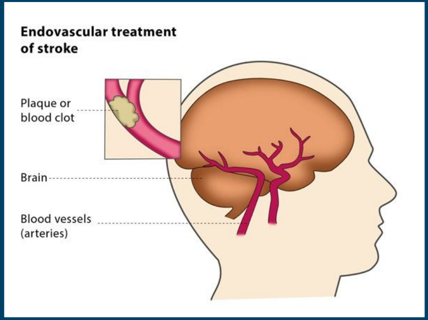
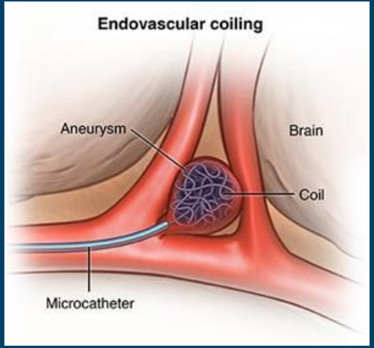
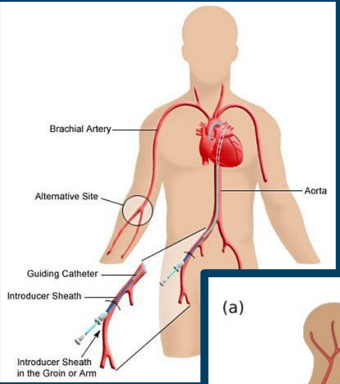
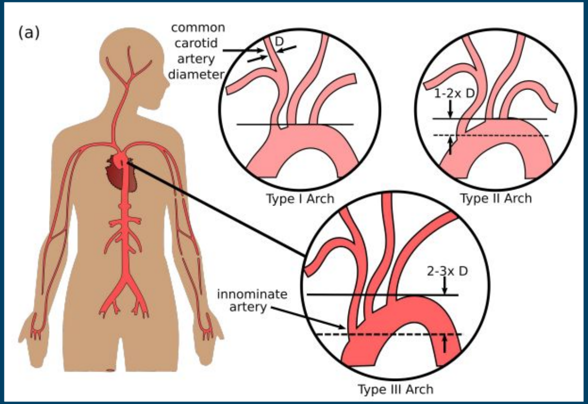
- Endovascular surgery is used to clear blood clots from inside the blood vessel (via catheterization)
- Typically, the catheter is inserted from the groin or arm and steered towards the heart
- To reach the cerebral circulation, the catheter has to pass through the aortic arch into the carotid artery
    - This involves complex pathways with acute turns



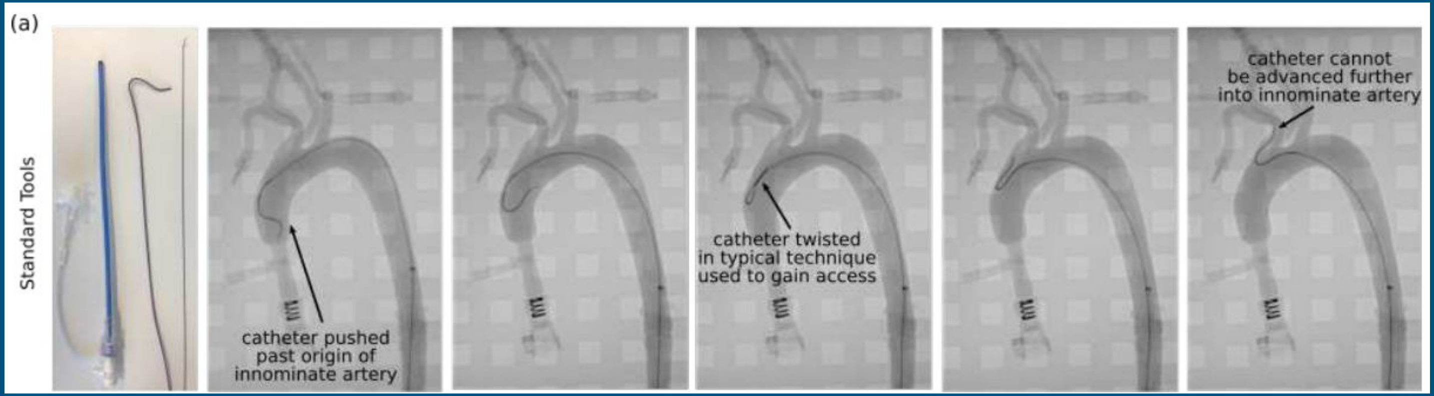


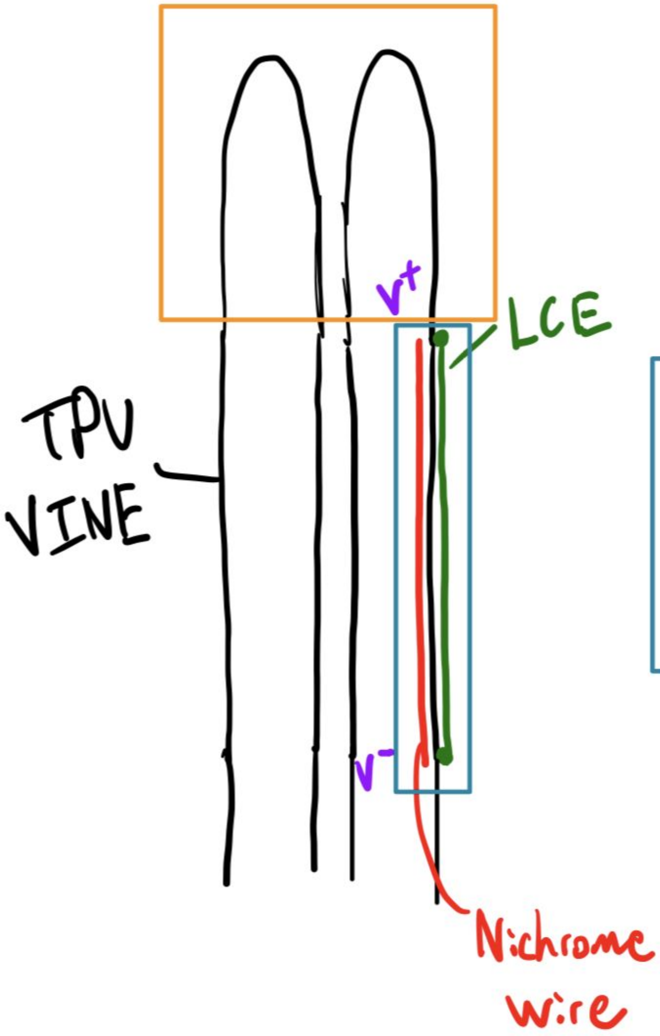


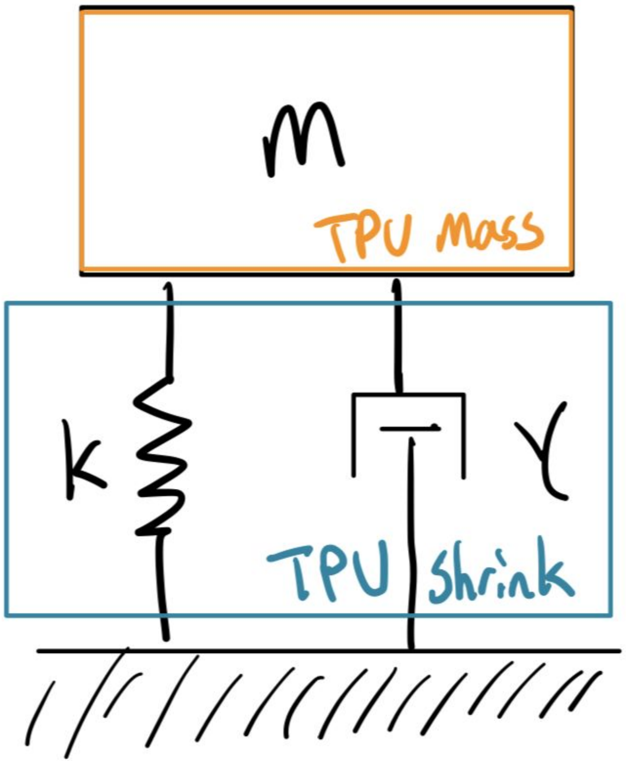


Problem

- Typical catheters must be pushed through tortuous vessels, which could cause damage through shear
- Standard catheters are also difficult to steer at the distal end, requiring surgeons to perform difficult maneuvers

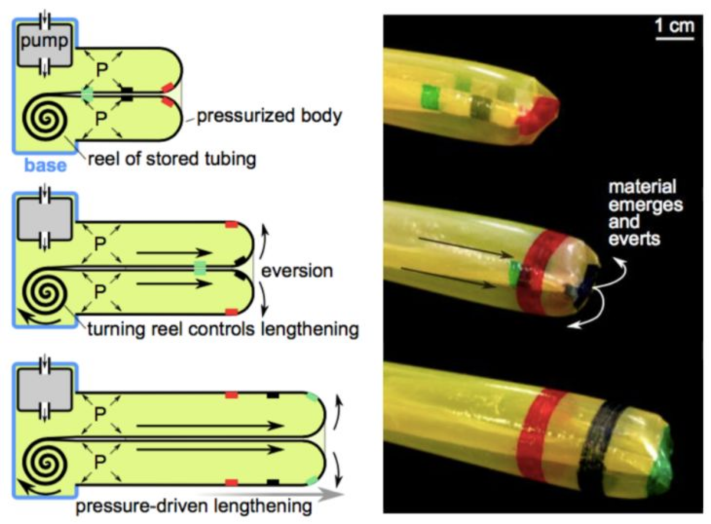


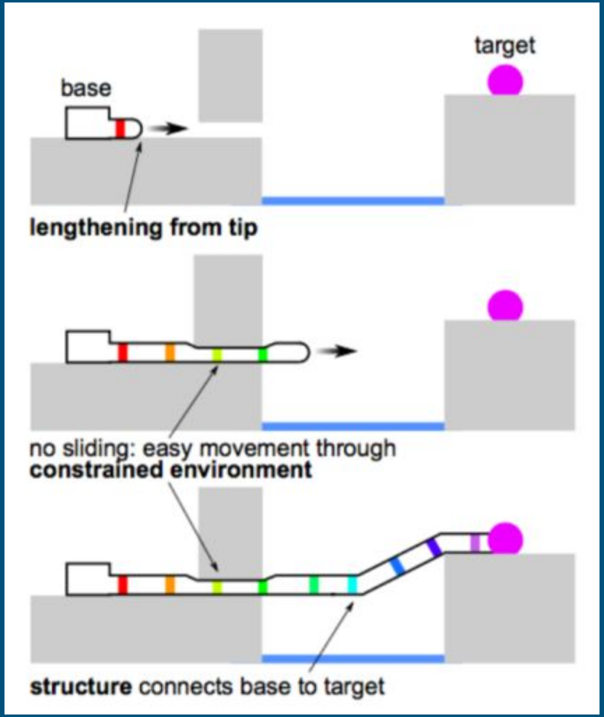

TPU VINE
V^+
LCE
V^-
Nichrome wire


m
TPU Mass
K
γ
TPU Shrink

Soft VINE Robots

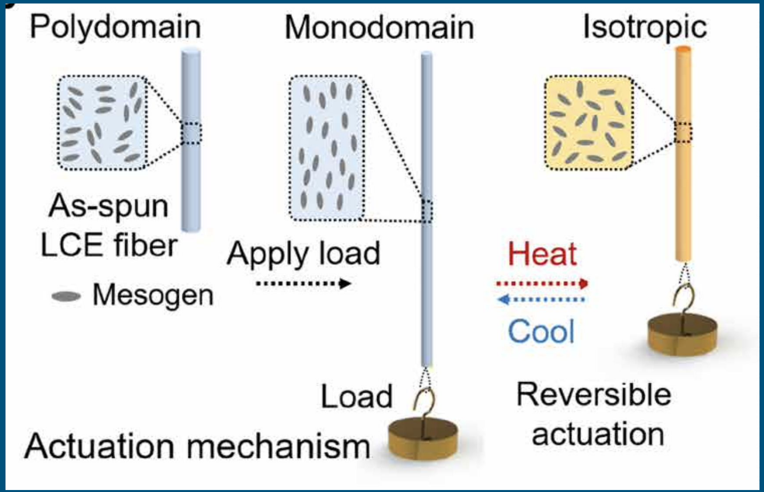
- **Vascular Internal Navigation by Extension (VINE)** catheter robots are able to grow through vessels by everting from the tip, causing very low shear.





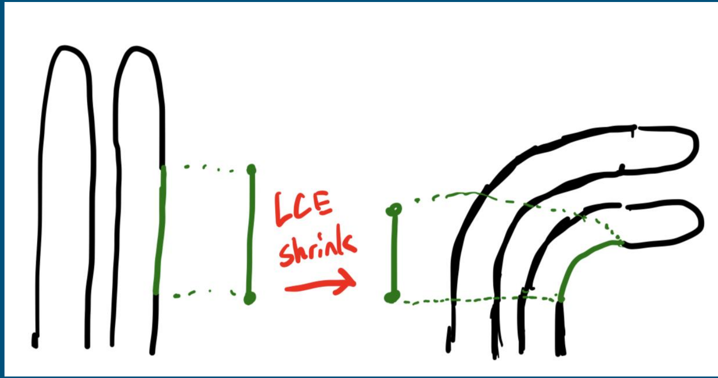
Steering the VINE through Liquid Crystal Elastomer (LCE)

- LCEs are made by layering As-spun LCE fibers to create contraction along one axis when heated
- The manufacturing process can be tuned to create an operating range close to body temperature:
  - **T_{lo} = 37**
  - **T_{hi} = 50**
  - T_{Bl} = 37



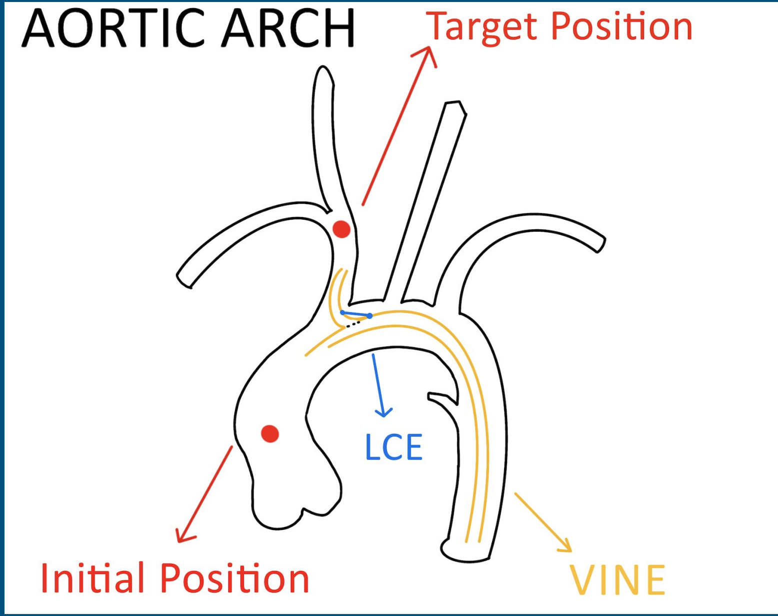
Steering the VINE through Liquid Crystal Elastomer (LCE)

- LCE will shrink when heated
- This causes the VINE to bend towards the contracted LCE
- Heating will occur through a voltage applied across embedded wires:
    - **$P = V^2/R$**



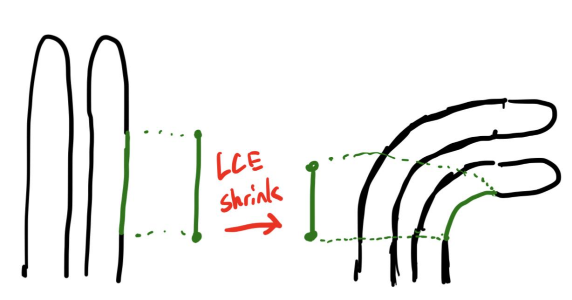
Operating Setpoint

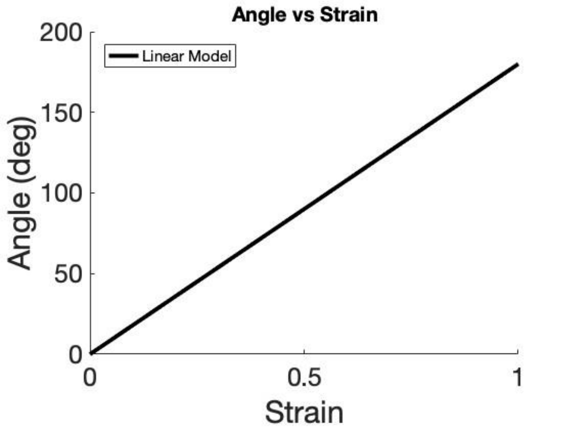
- We will be using the uppermost (carotid) artery as the target which will be the setpoint in the controller
- The vine will first need to be raised from its initial position then continually adjust to the final location
- Error will be distance from target:
  - **e = u_target - u_measured**



Modeling the Actuation

- Assume the strain applied is in one dimension, proportional to (u)
- Assume the strain applied is linearly proportional to curvature, where a strain of 0 is 0 degree curve, and a strain of 1 is 180 degree curve





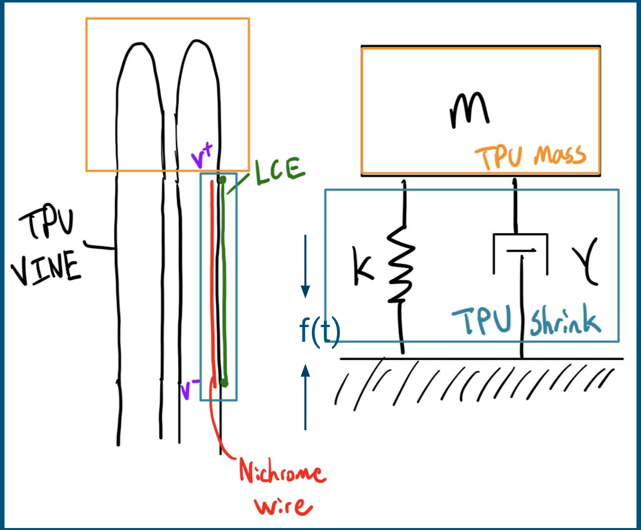
The VINE as a spring-mass damping system

Spring-damper component: Shrinking part of vine with LCE attached (blue)

- Known elasticity of Thermoplastic polyurethane (TPU)
  - Spring constant: **k**
- Wide range of properties via different compositions
  - Damping coefficient: **gamma**

Mass component: Movable tip portion of VINE (orange)

- Known density and geometry of section
  - Mass: **m**



$$m_{TPU}\frac{dv}{dt} = -ku - \gamma v + f(t)$$

$$v = \frac{du}{dt}$$

TPU characterization

Thickness: 0.0000381 m

Length of bending segment: 2 cm = 0.02 m

Length ahead: 1 cm = 0.01 m

OD 5 mm -> circumference: 0.0157m -> volume = 0.00000000598 m^3

ID 4 mm -> circumference: 0.0126m -> volume = 0.00000000480 m^3

Density = 1.28 g/cc = 1280000 g/m^3

Total TPU mass to move = 0.138 g (density * total volume)

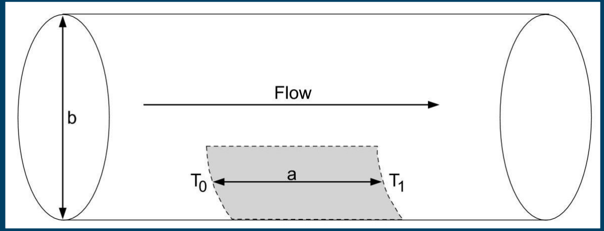
E = 39000000 Pa (TPU property)

A = 0.0000006 m^2

L = 0.02 m;

K = AE/L = 1170 Pa * m = 1170 N/m (spring constant)

Heat Transfer Coefficient for Blood Flow



$$h = \frac{\rho c u (T_1 - T_0) b}{[0.25(2T_s + T_1 + T_0) - T_m] a}$$

h = 32.96017 W/(m^2*K)
h = 0.0103 W/K (0.000314 m^2 of contact with blood)

$$h_{bl}(T - T_{bl})$$

ρ (blood density)	1000 kg/m^3 [2]
c (blood specific heat)	4180 J/kg·K [2]
u (mean blood velocity)	0.18 m/s [3]
T_0 (Inlet temp.)	37 ℃ [2]
T_1 (outlet temp.)	37.05 ℃ [2]
T□ (max temp.)	50 ℃ [2]
T□ (medium temp.)	37.025 ℃
a (length of the heated region)	0.02 m
b (diameter of heated region)	0.0049 m

Paper Reference

Assumptions and Parameters

Assumptions:

1. The amount of heat transferred to the LCE linearly affects the rate of curving.

Symbol	SI Values	Source
c_{LCE}	1570 J/kg*K	LCE specific heat [1]
V_{LCE}	$1.2 * 10^{-7}$ m^3	Volume
m_{LCE}	$1.5 * 10^{-4}$ kg	Volume times density
h_{BL}	0.0103 W/K	H.T. Model
k	1170 N/m	TPU Spring
γ	100 Ns/m	100 Ns/m
m_{TPU}	0.000138 kg	Thin film TPU density
T_{BL}	310.15 K	Body temperature
T_{low}	310.15 K	LCE operating point
T_{high}	323.15 K	LCE operating point
β	23.4 N	LCE manufacturing
α	0.0000537	Power Coefficient

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System Equations

$$m_{LCE} c_{LCE} \frac{dT}{dt} = \alpha P - h_{bl}(T - T_{bl})$$

$$v = \frac{du}{dt}$$

$$m_{TPU} \frac{dv}{dt} = -ku - \gamma v + \beta\left(\frac{T - T_{low}}{T_{high} - T_{low}}\right)$$

System Equations

LCE Heating | Input Power | Heat Loss from Blood Flow

$$m_{LCE}c_{LCE}\frac{dT}{dt} = \alpha P - h_{bl}(T - T_{bl})$$

$$v = \frac{du}{dt}$$

Position

Velocity | Spring | Damping | Force LCE contracts

$$m_{TPU}\frac{dv}{dt} = -ku - \gamma v + \beta\left(\frac{T - T_{low}}{T_{high} - T_{low}}\right)$$

LaPlace Transform

1. $$m_{LCE}c_{LCE}\left(sT(s) - T_0\right) = \alpha P(s) - h_{bl}T(s) - h_{bl}T_{bl}$$

2. $$su(s) - u_0 = v(s)$$

3. $$m_{TPU}\left(sv(s) - v_0\right) = -ku(s) - \gamma v(s) + \beta\left(\frac{T(s) - T_{low}}{T_{high} - T_{low}}\right)$$

Transfer Function

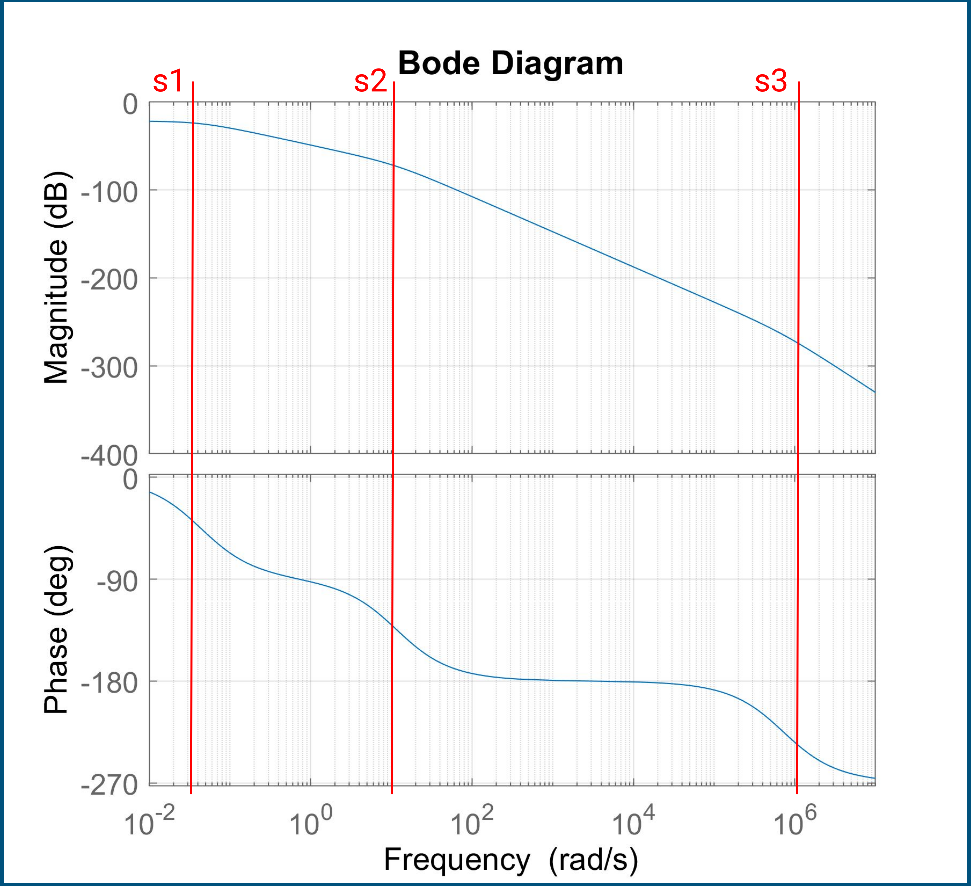
$$u(s) = \frac{\alpha\beta}{T_{high} - T_{low}} \frac{1}{\left(m_{LCE}\, c_{LCE}\, s + h_{bl}\right)\left(m_{TPU}\, s^2 + \gamma s + k\right)} P(s)$$

Poles and Bode Plot

Poles:
s = −0.0437, -11.702, -724520

Bad bandwidth, DC gain, and phase margin

We need Proportional, Integral, and Derivative control



PID Control

Proportional to lift magnitude

Integral at first pole: infinite gain at DC

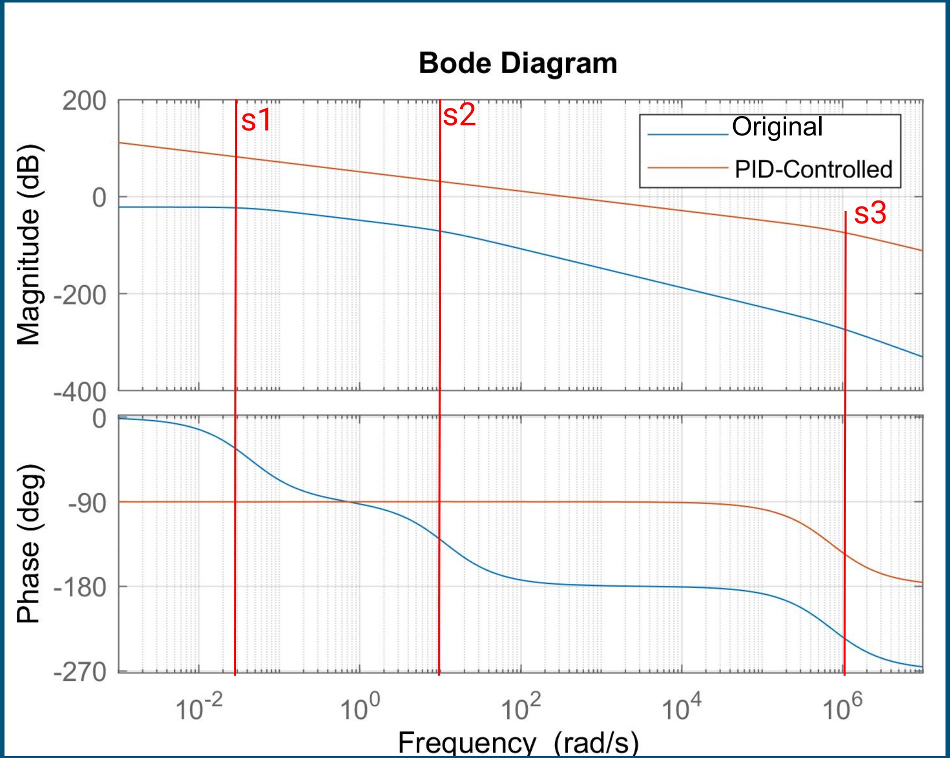
Derivative at second pole: improve phase margin

Ki/Kp = 0.0437; kp/kd = 11.702

Kp =100000; ki = 4370; kd =8545

Bandwidth: 370 rad/s

Phase margin: 90



PID Controller

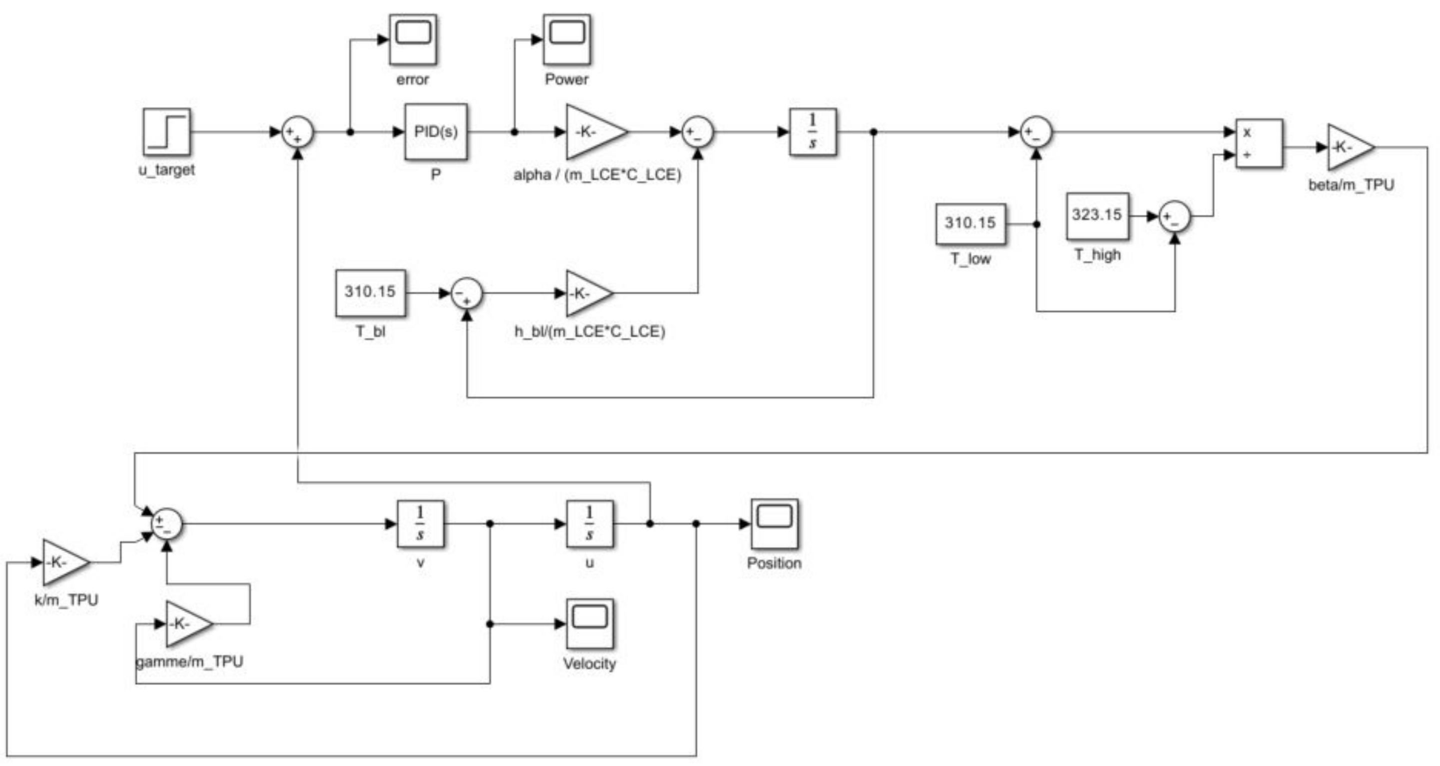
$$e(t) = u_{target}(t) - u_{meas}(t)$$

$$P(t) = K_p e(t) + K_d \frac{de}{dt} e(t) + Ki \int e(t)\, dt$$

$$P(t) = K_p\left(u_{target}(t) - u(t)\right) + K_d \frac{d}{dt}\left(u_{target}(t) - u(t)\right) + K_i \int \left(u_{target}(t) - u(t)\right) dt$$

$$K_p = 100000,\ K_d = 4370,\ K_i = 8545$$

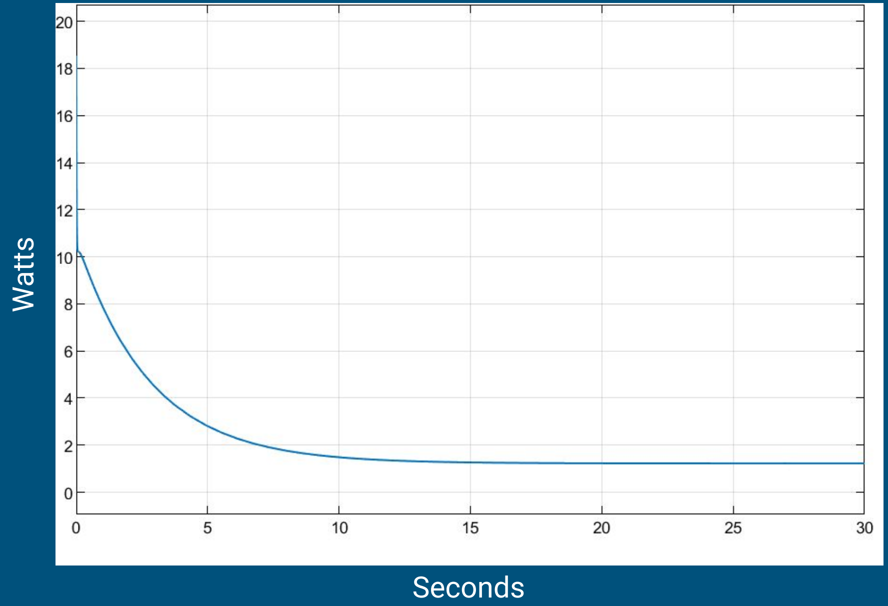
Block Diagram: Simulation 1



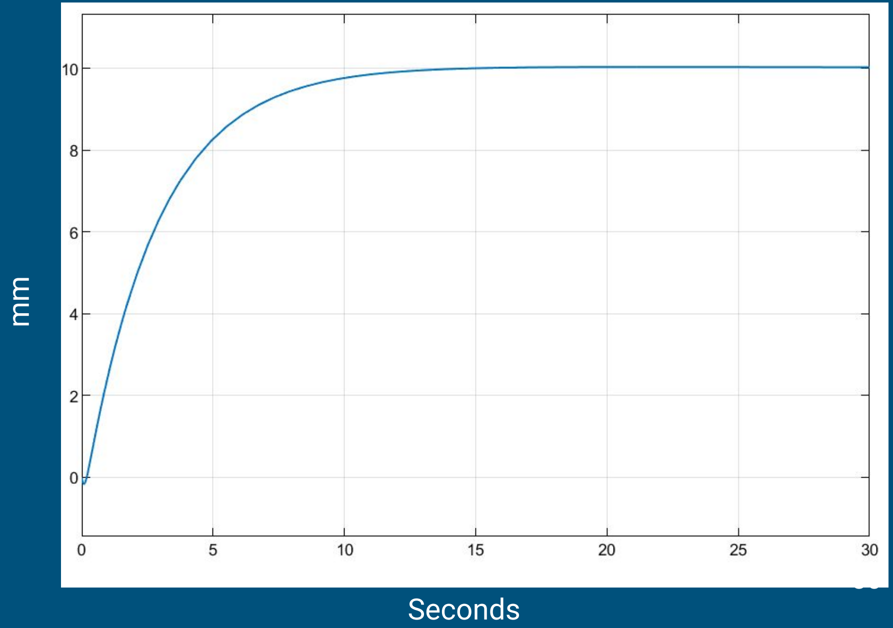
Responses

For example, if we consider u to start at 0 and u_target to be 10 mm

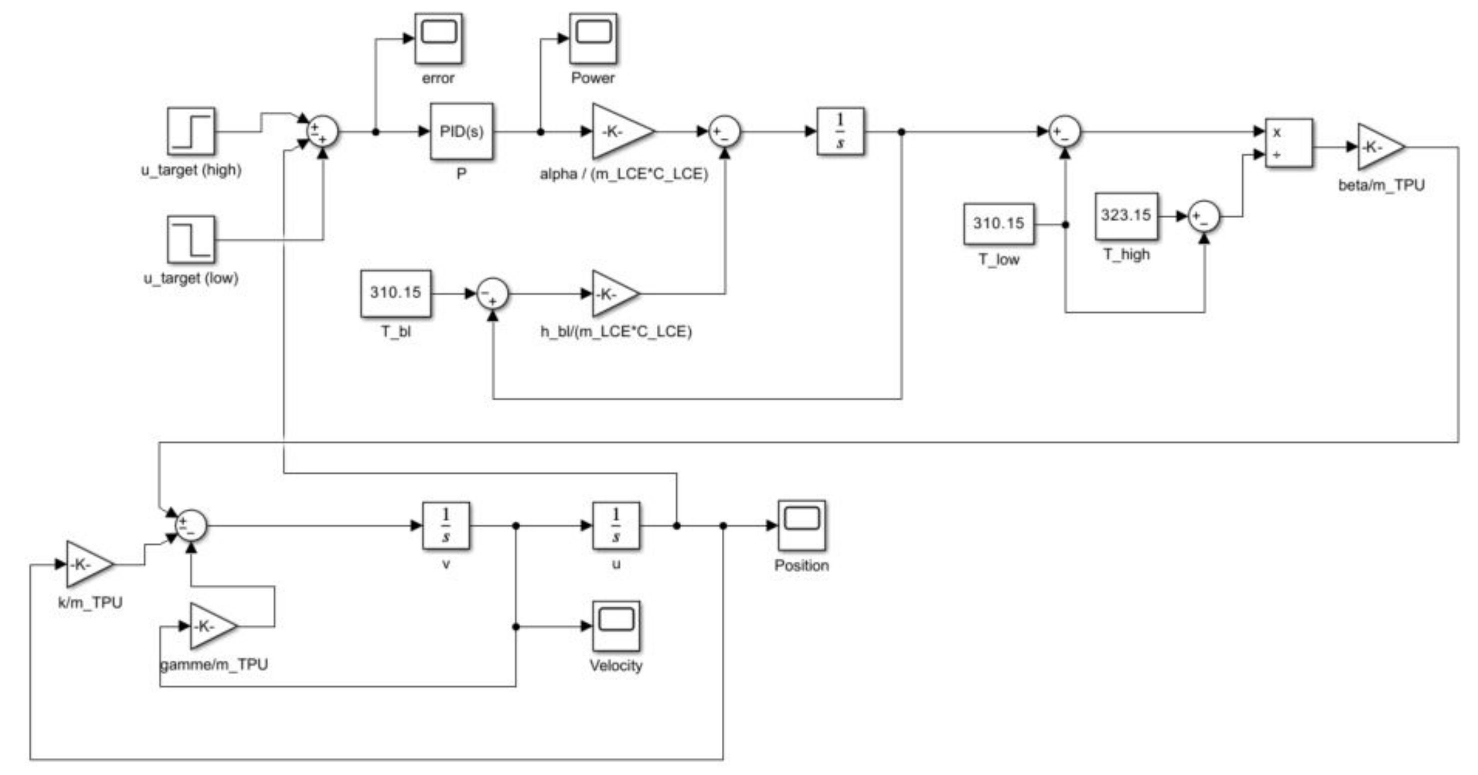
Power (P)



Position (u_m)



Block Diagram: Simulation 2



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- Our estimation for the **damping coefficient, alpha, and beta** values could be inaccurate.
- The **time** it takes to **heat wire** is not **instantaneous**
- LCE may take time to **actuate and cool down** (although blood flow may be high)

Limitations

- Simplification of Biosystem
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  - **Nonlinear** and **time-varying** properties not fully captured.

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  - Vine modeled as a spring-mass system **simplifies** complex biological tissues.
  - **Nonlinear** and **time-varying** properties not fully captured.
- Real blood flow involves complex **fluid dynamics** not fully represented.
- Estimation may not account for **variations in temperature** distribution within the vine.

Active Target Positioning

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- Active target positioning is crucial for reaching specific cardiac chambers or vessels affected by blood flow dynamics.
- The ability to **actively adjust** the target position based on real-time feedback in situations where the anatomical landscape may shift, such as in regions with pulsatile blood flow.
- Allows the vine robot to **navigate through dynamic environments** influenced by blood flow changes.

Thank You!

Sources

[1] Cang, Yu, et al. “On the Origin of Elasticity and Heat Conduction Anisotropy of Liquid Crystal Elastomers at Gigahertz Frequencies.” Nature News, Nature Publishing Group, 6 Sept. 2022, www.nature.com/articles/s41467-022-32865-1.

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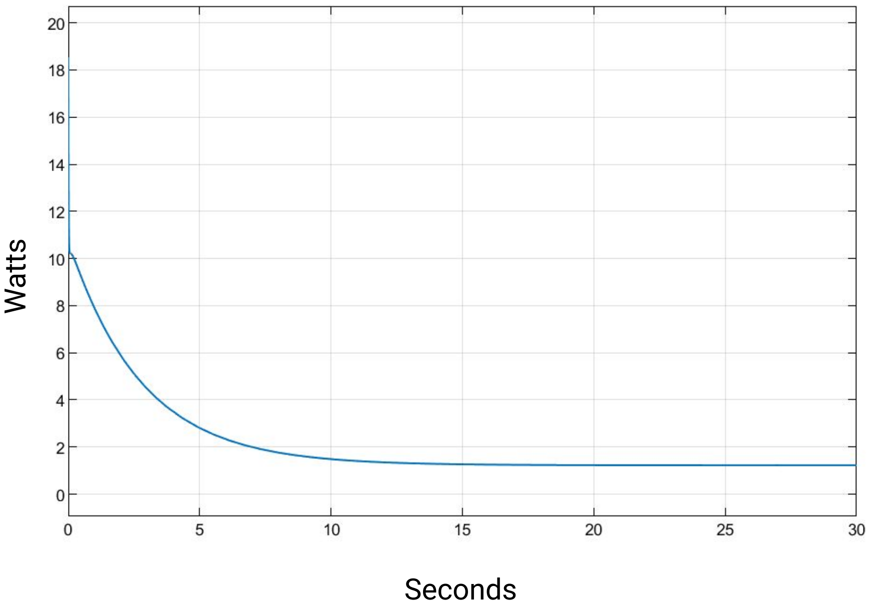
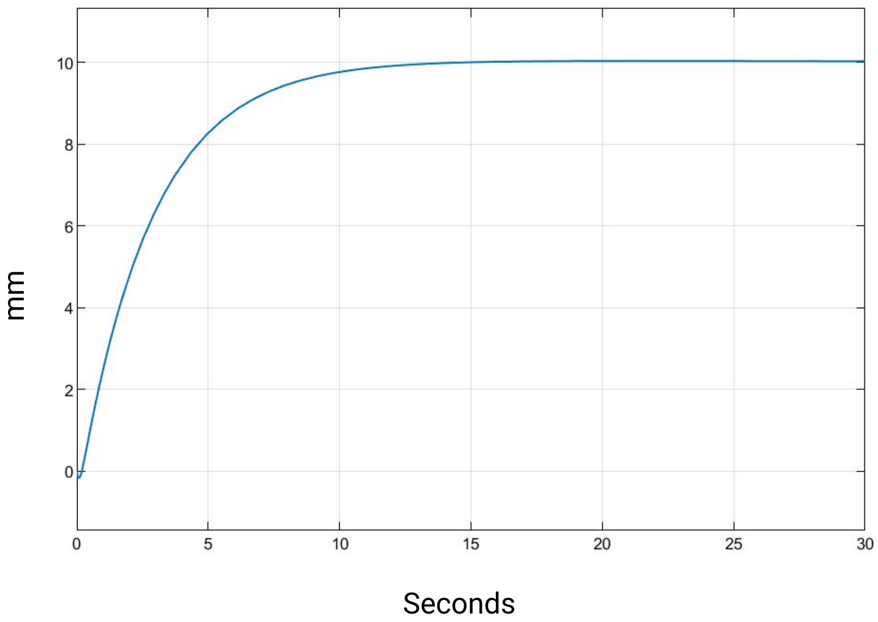
For example, if we consider u to start at 0 and u_target to be 10 mm

Power (P)



Position (u_m)

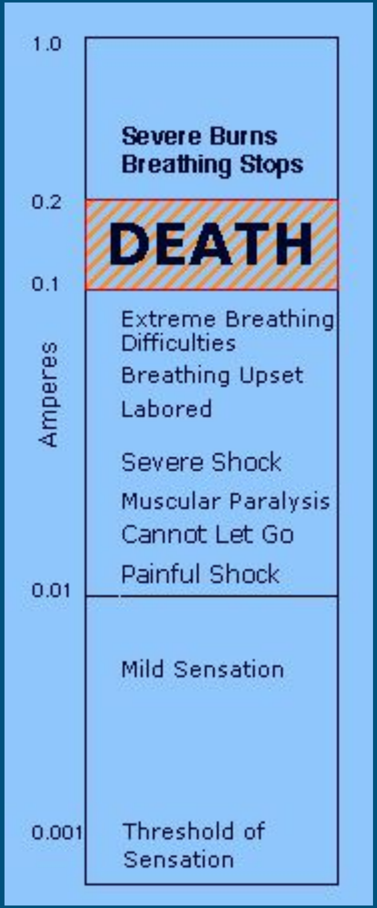


Responses

For example, if we consider u to start at 0 and u_target to be 10 mm

Danger Amps!!!!

https://www.asc.ohio-state.edu/physics/p616/safety/fatal_current.html



Results

Our controller takes 15 seconds to fully change position

TODO

- Output plots from Simulink for Vin and u
- Discussion/conclusion
- …

Proposed VINE Robot

- Vascular Internal Navigation by Extension (VINE) catheter robots are able to grow through vessels by everting from the tip, causing very low shear.

the surface of the brain may be accessed in this manner. These procedures are typically performed under X-ray fluoroscopy to enable real-time visualization and ensure proper guidance.

Assumptions and Parameters

Assumptions:

1. The amount of heat transferred to the LCE linearly affects the rate of curving.
2. The damping coefficient is assumed to be ? Ns/m, based on an educated guess.
3. The mass of the TPU was approximated by accounting the thickness, circumference, and length of the TPU vine
4. Tissue destruction occurs when the temperature exceeds 50 degrees Celsius, so we assume the temperature at which the LCEs will actuate will be 40 - 50 degrees Celsius

Table of parameters:

ρ_{LCE}	$1.0 \frac{g}{cm^3}$
C_{LCE}	$1.5 \frac{J}{gcm}$
h_{Bl}	?
R	$112\ \mu\Omega cm$
γ	100 Ns/m ?
$\backslash m_{TPU}$	0.138g ?
T_{Bl}	$37C$
T_{low}	$35C$
T_{high}	$45C$
alpha	N of force per (guess)

I didnt want to delete the other ones just in case >_<

New equations (need to paste them in)

$$V(t) = K_p e(t) + K_d \frac{de}{dt} e(t)$$

Laplace

$$sT(s) - T_{init} = \frac{2\kappa\sqrt{Rh_{Bl}\left(T_0 - T_{Bl}\right)}}{\rho_{LCE} c_{LCE} R} v_{in}(s) - h_B T(s)$$

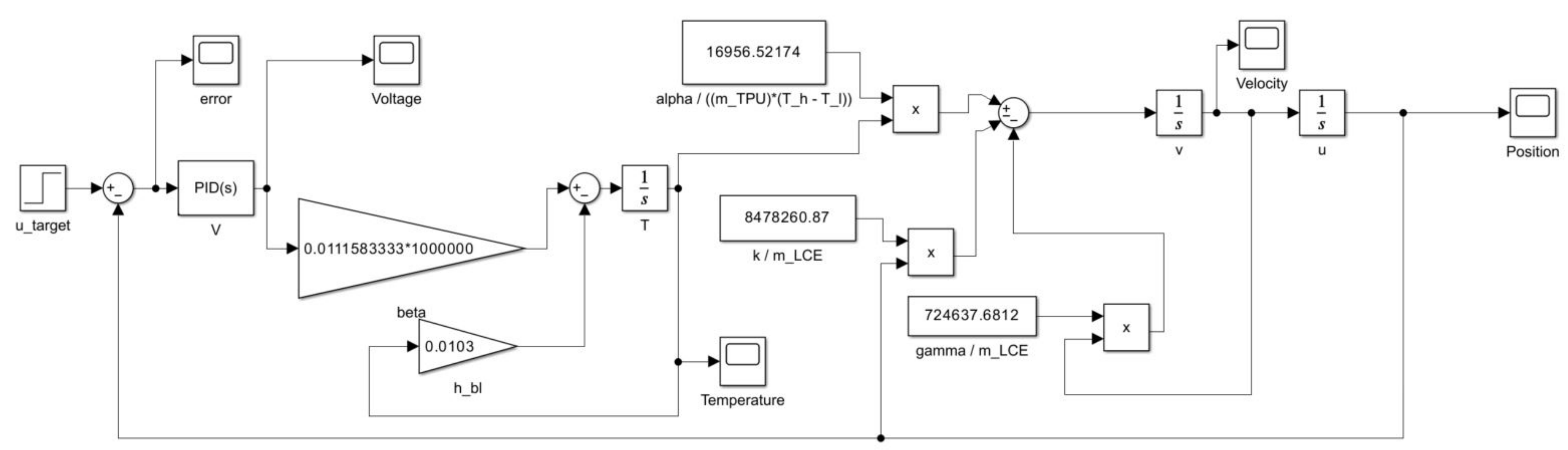
$$sv(s) - v_{init} = -\frac{k}{m} u(s) - \frac{\gamma}{m} v(s) + \frac{\alpha}{m} \frac{T(s)}{T_{high} - T_{low}}$$

Transf
er func

$$u(s) = \frac{\alpha\kappa\beta}{\left(T_{high} - T_{low}\right)\left(m_{TPU} s^2 + \gamma s + k\right)\left(s + h_{bl}\right)} V(s)$$

$$V(t) = K_p\left(u_{target}(t) - u(t)\right) + K_d \frac{d\left(u_{target}(t) - u(t)\right)}{dt}\left(u_{target}(t) - u(t)\right)$$

Block Diagram



Block Diagram