

Smart Hand - 2

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Group 1

Presentation Overview

- Motivation & Area of Focus (Recap)
- Change in Scope & New Goals
- Literature Review
- Design Requirements
- Actuation System Background
- Preliminary Analysis
- Future work
- Q&A

Motivation & Area of Focus

- There is a large need to develop improved prosthetic devices with a particular focus on robotic hands.
- Our complex hand motions are difficult to recreate and result in bulky devices. Rejection rate of 34%.
- Can piezoelectric actuation address this need?
 - **Plus:** High force output and simplistic nature.
 - **Cons:** Displacements are very small.

(Braza et al., 2020)

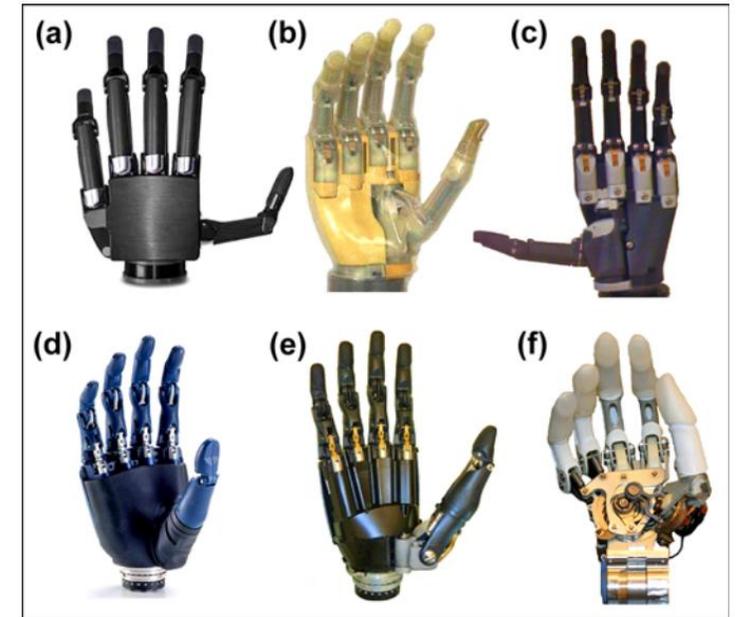


Figure 1. (a) Vincent hand by Vincent Systems, (b) iLimb hand by Touch Bionics, (c) iLimb Pulse by Touch Bionics, (d) Bebionic hand by RSL Steeper, (e) Bebionic hand v2 by RSL Steeper, and (f) Michelangelo hand by Otto Bock. All hands shown without cosmetic glove.

(Belter et al., 2013)

Project Scope & Goals

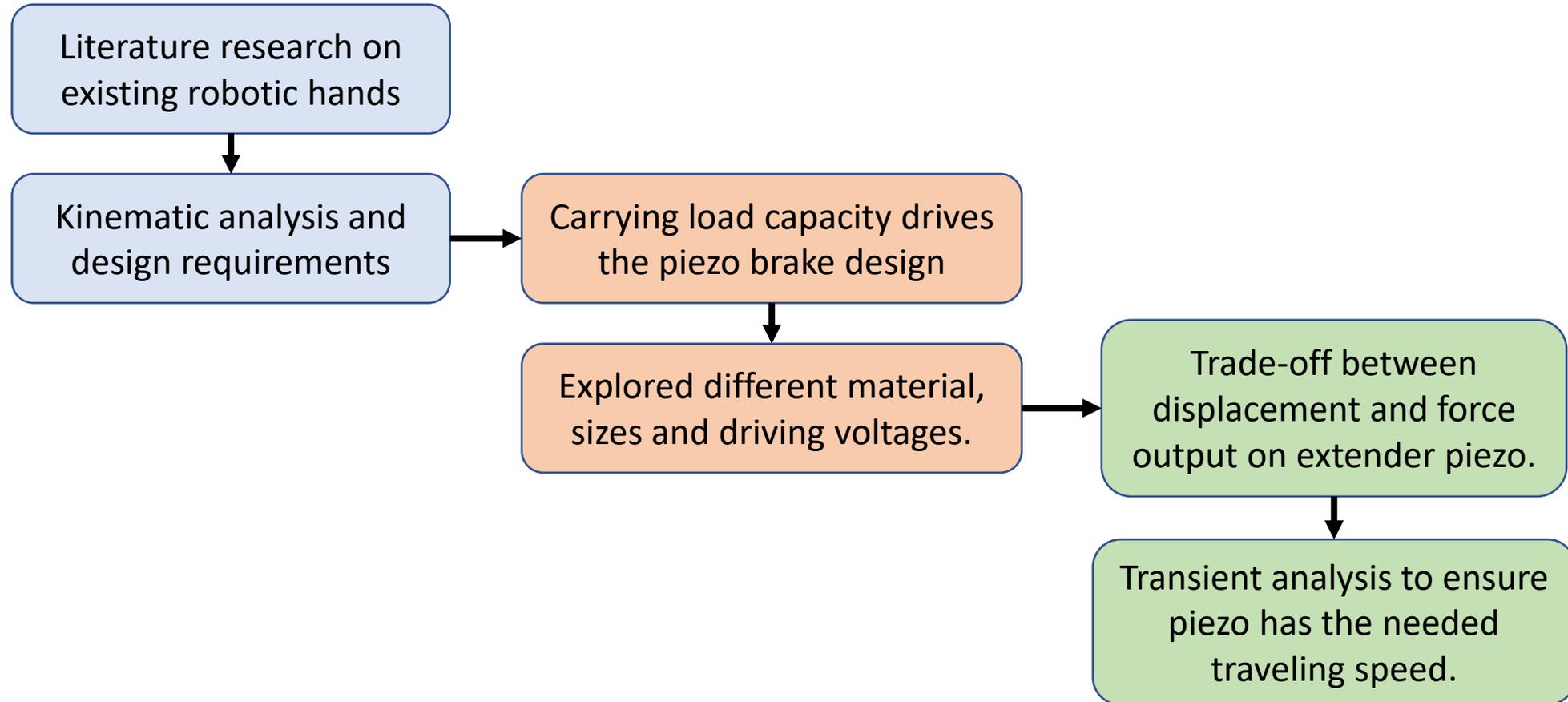
Previous Scope:

- Design a prosthetic hand to leverage unique properties of piezoelectric actuators.
 - Kinematic design of finger linkages
 - Design piezo actuation system

Current Scope:

- Design a piezoelectric actuation system that can power a single joint.
- Selected actuation: **Inchworm**
 - Not restricted by the range of motion limitation.
 - Relatively fast movement speed.
 - Sufficiently large load bearing capacity.

Overarching Goals



Existing Piezoelectric Research

Design and Control of a Robotic Thumb Using Piezoelectric Actuators

- Designed by an undergraduate MIT student, this project undertook the development a single DOF thumb using a hybrid DC motor/piezo actuator system

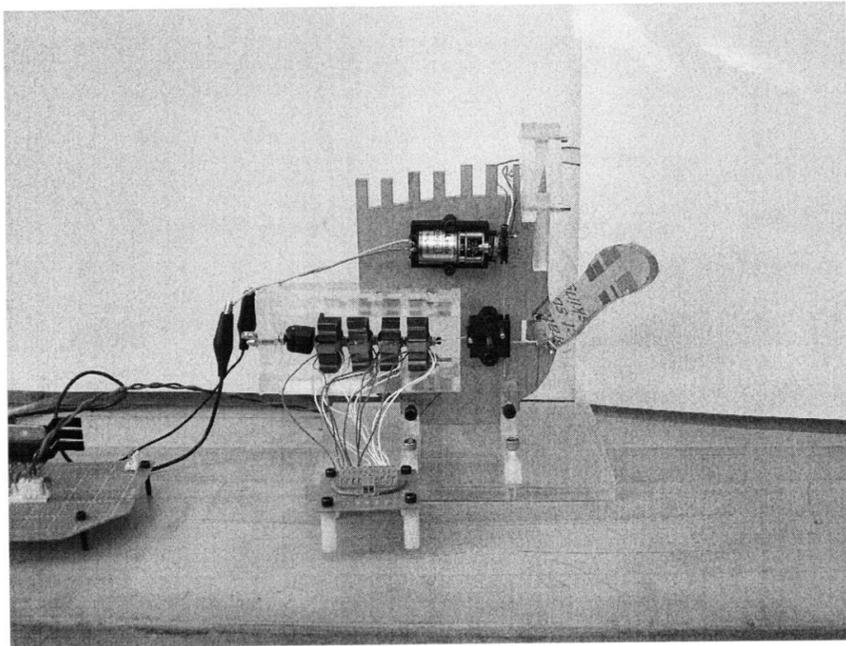


Figure 11. Front view of fully assembled hybrid DC motor/PZT actuator prototype.

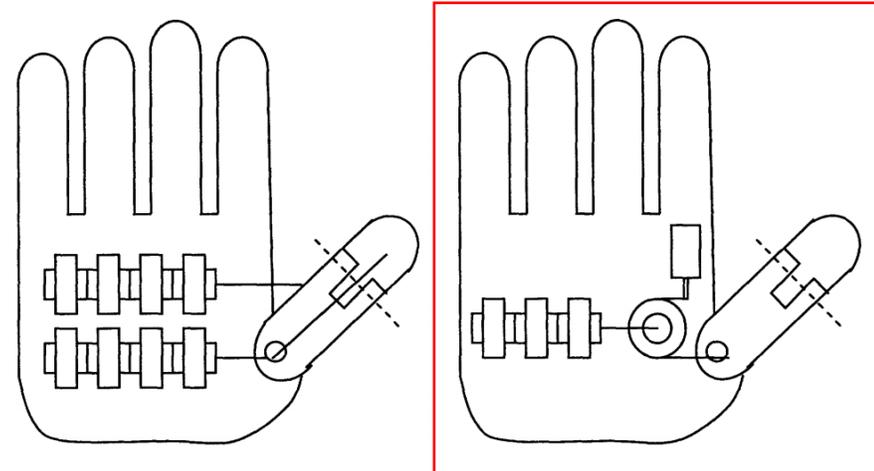


Figure 10. Potential design implementations: PZT actuator driven (left), hybrid DC motor/PZT actuator(right).

(Levinson, 2009)

Existing Piezoelectric Research

Design and Control of a Robotic Thumb Using Piezoelectric Actuators

- Aimed to achieve a 90-degree range of motion with a max pinching force of 10 N
- Implemented a "tendon" style design with DC motor used to achieve the majority of motion (0 – 90 deg) while the piezo actuator was used to achieve fine motion control (0 - 10 deg)

Existing Piezoelectric Research

Design and Control of a Robotic Thumb Using Piezoelectric Actuators

- Shortcomings:
 - Limited range of motion from piezo actuators (10 degrees)
 - Selected piezo actuators had a max force output of 5 N
 - Force losses associated with routing of tendon in addition to attachment point of tendon to thumb resulted in max gripping force of only 0.35 N

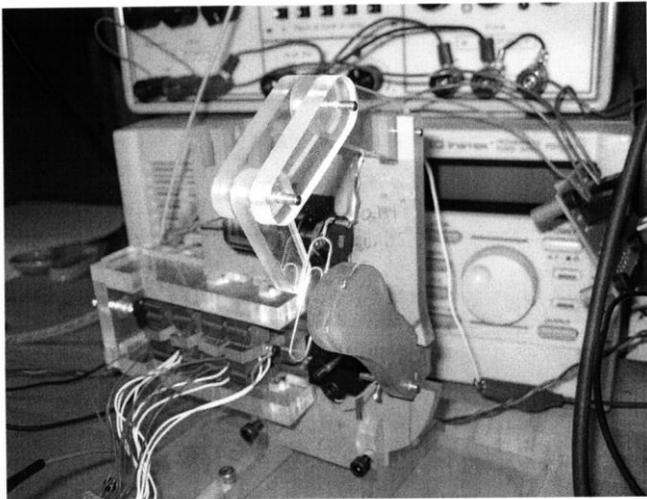
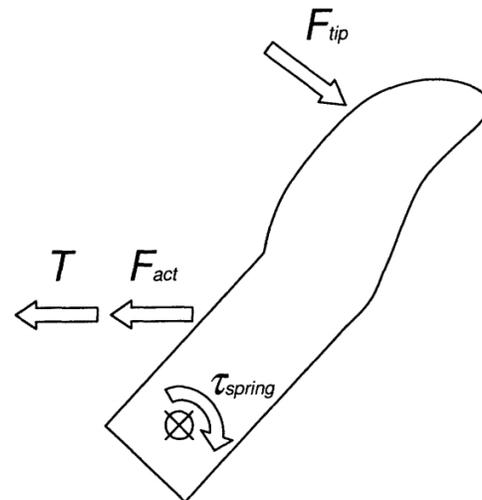


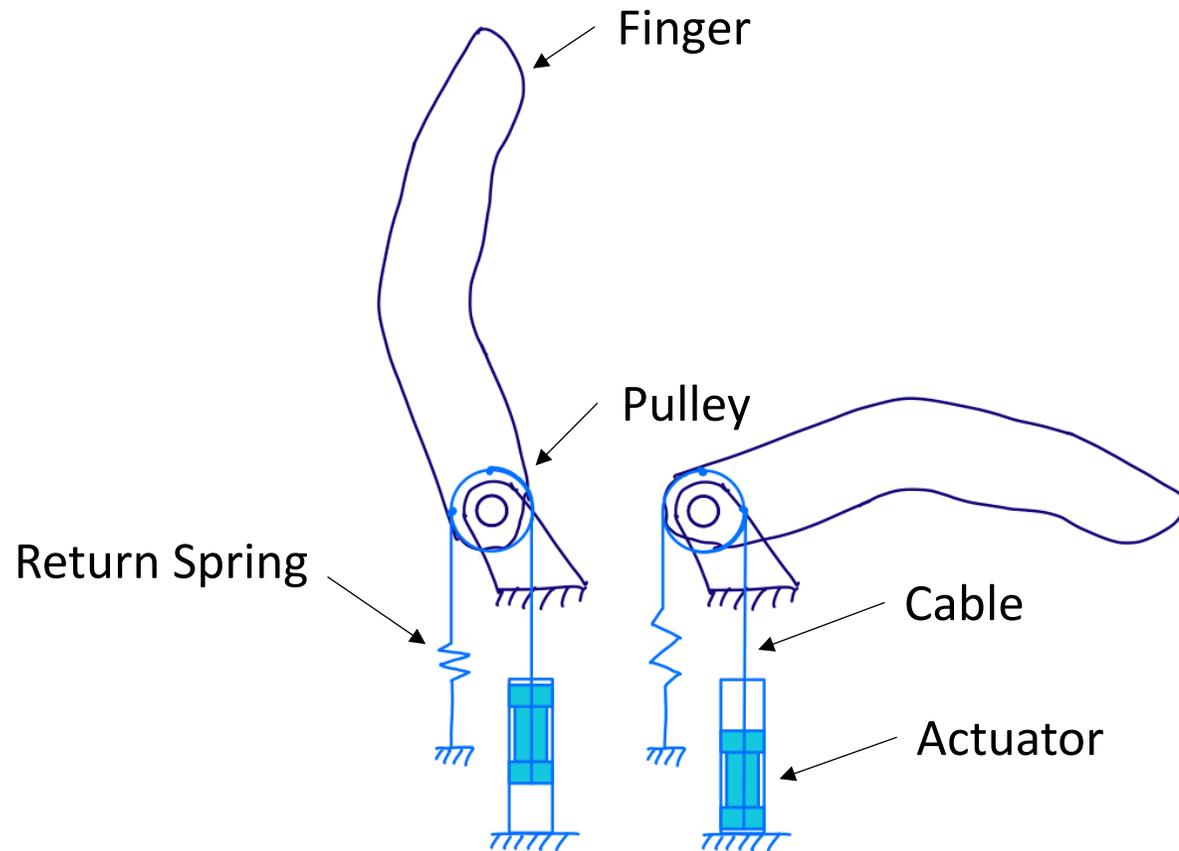
Figure 17. Thumb prototype pinching a paperclip.



(Levinson, 2009)

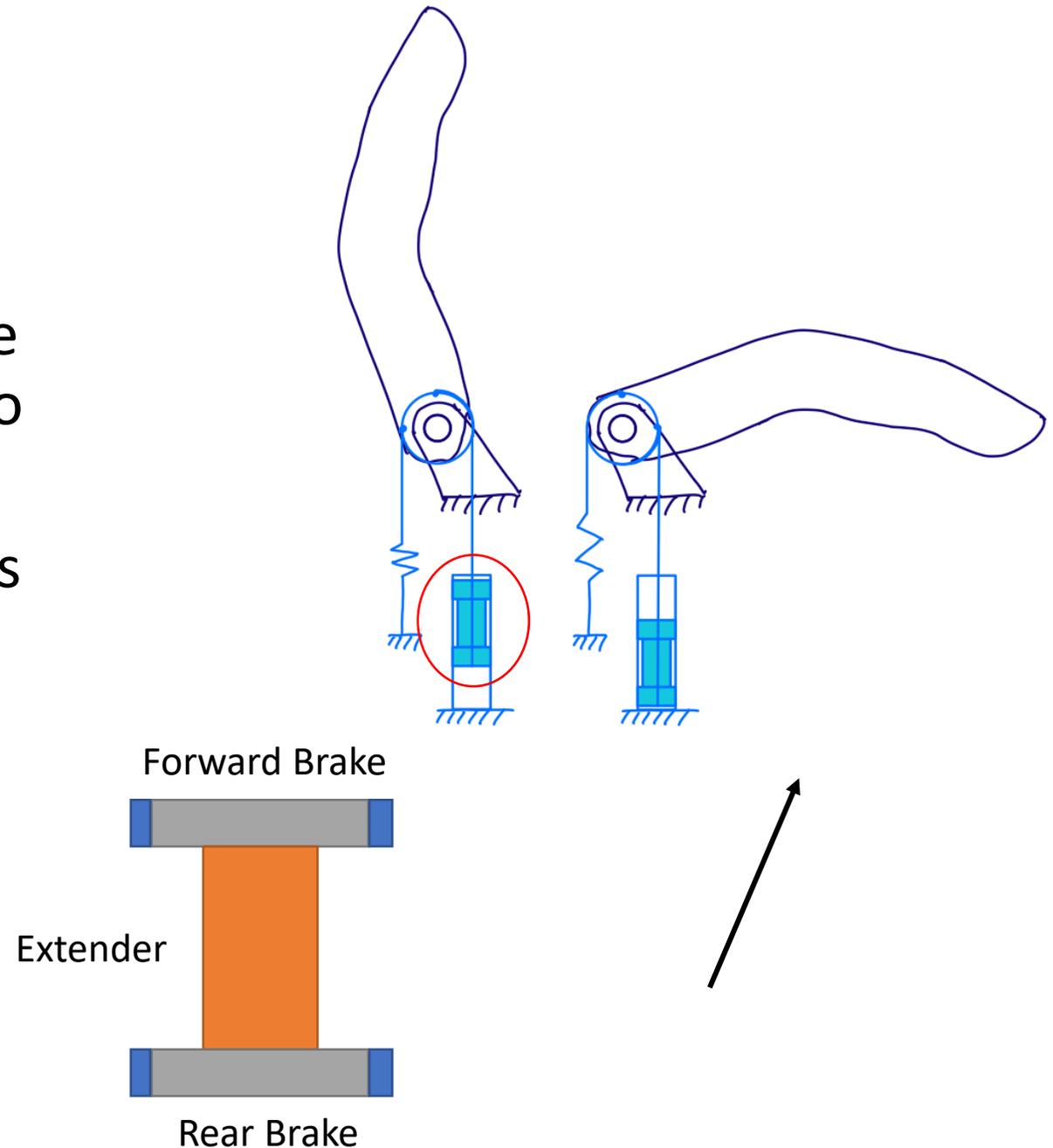
Finger Kinematics

- Focus on a single, rigid finger

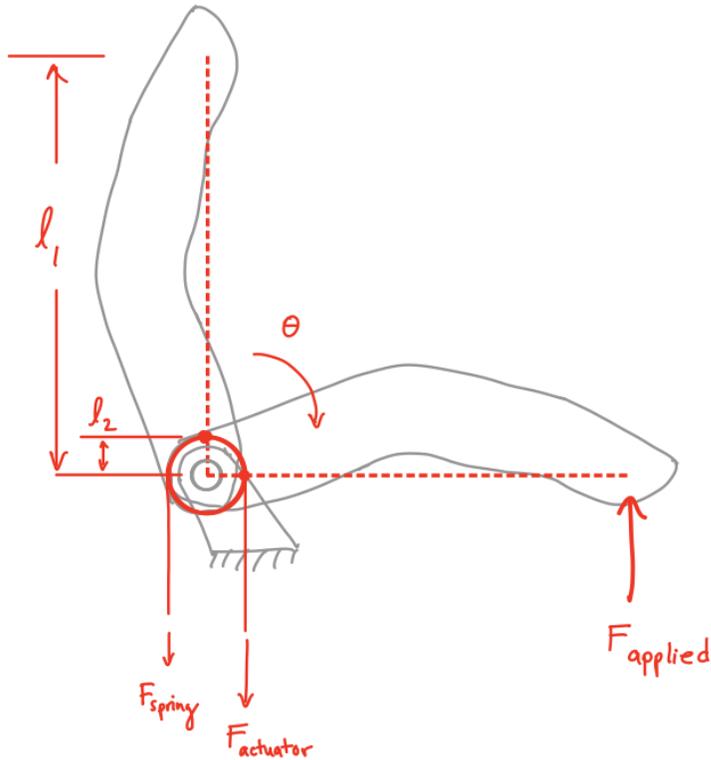


Proposed Approach

- Focus on the inchworm and use the analyses we have learned in class to design the 'ideal' actuator.
- Develop a series of Excel calculators that allows us to quickly iterate on different piezo properties.
- Focus on the two brakes and extender.



Finger Kinematics



$$\sum M = F_{applied} \times l_1 + F_{spring} \times l_2 - F_{actuator} \times l_2$$

$$\Leftrightarrow F_{actuator} = F_{applied} \times \frac{l_1}{l_2} + F_{spring}$$

Also,

$$F_{spring} = \Delta l_{spring} \times k_{spring} + F_{spring, pretension}$$

$$\Delta l_{spring} = -\Delta l_{actuator} = l_2 \times \pi \times \frac{\theta [deg]}{180}$$

If $l_1 =^{**} 80 \text{ mm}$, $l_2 = 5 \text{ mm}$, $\theta = 90 \text{ deg}$, $F_{applied} = 10 \text{ N}$, $k_{spring} = 0.76 \frac{\text{N}}{\text{mm}}$, $F_{spring, pretension} = 1 \text{ N}$:

**based on approximate length of pointer finger

$$\Rightarrow F_{actuator} = 167 \text{ N}$$

$$\Rightarrow \Delta l_{actuator} = 7.85 \text{ mm}$$

Also, for $\dot{\theta} = 100 \frac{\text{deg}}{\text{s}}$ (ideal actuation speed according to Belter et al., 2013):

$$\Rightarrow \text{actuation speed} = 8.73 \text{ mm/s}$$

Spring Selection

- Looking at springs which will satisfy the spring requirement equation derived on the previous slide, will attempt to source the spring with the lowest spring constant (k_s), to reduce the load of the actuator.

- This satisfies the spring equation:

$$7.854\text{mm} \times \left(0.7562 \frac{\text{N}}{\text{mm}}\right) + 1 = 6.937624 \text{ N} < 12.455 \text{ N}$$

- This spring is compact and meets our requirement...

$$k_s = 0.7562 \frac{\text{N}}{\text{mm}}$$

McMASTER-CARR®

Find

Compression Springs

25.5 mm Long



Packs of 5 In stock
\$10.36 per pack of 5
94125K525

ADD TO ORDER



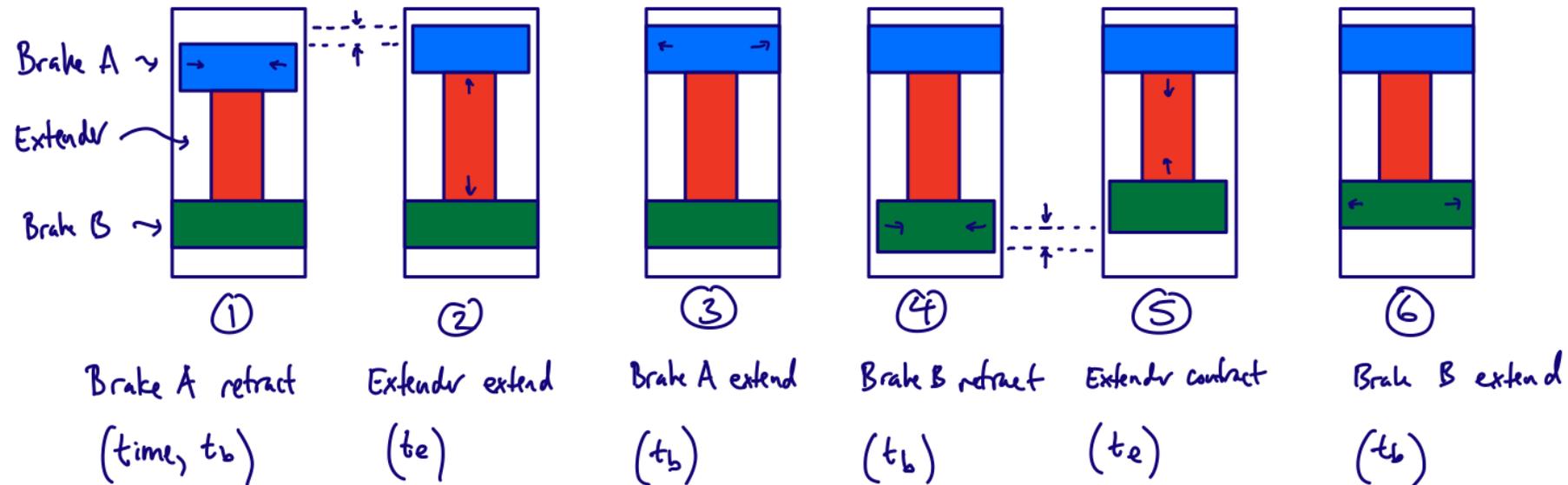
3-D Solidworks

Download

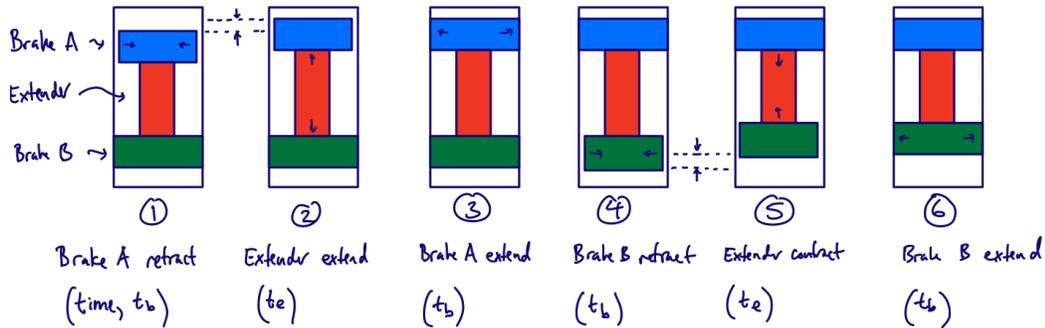
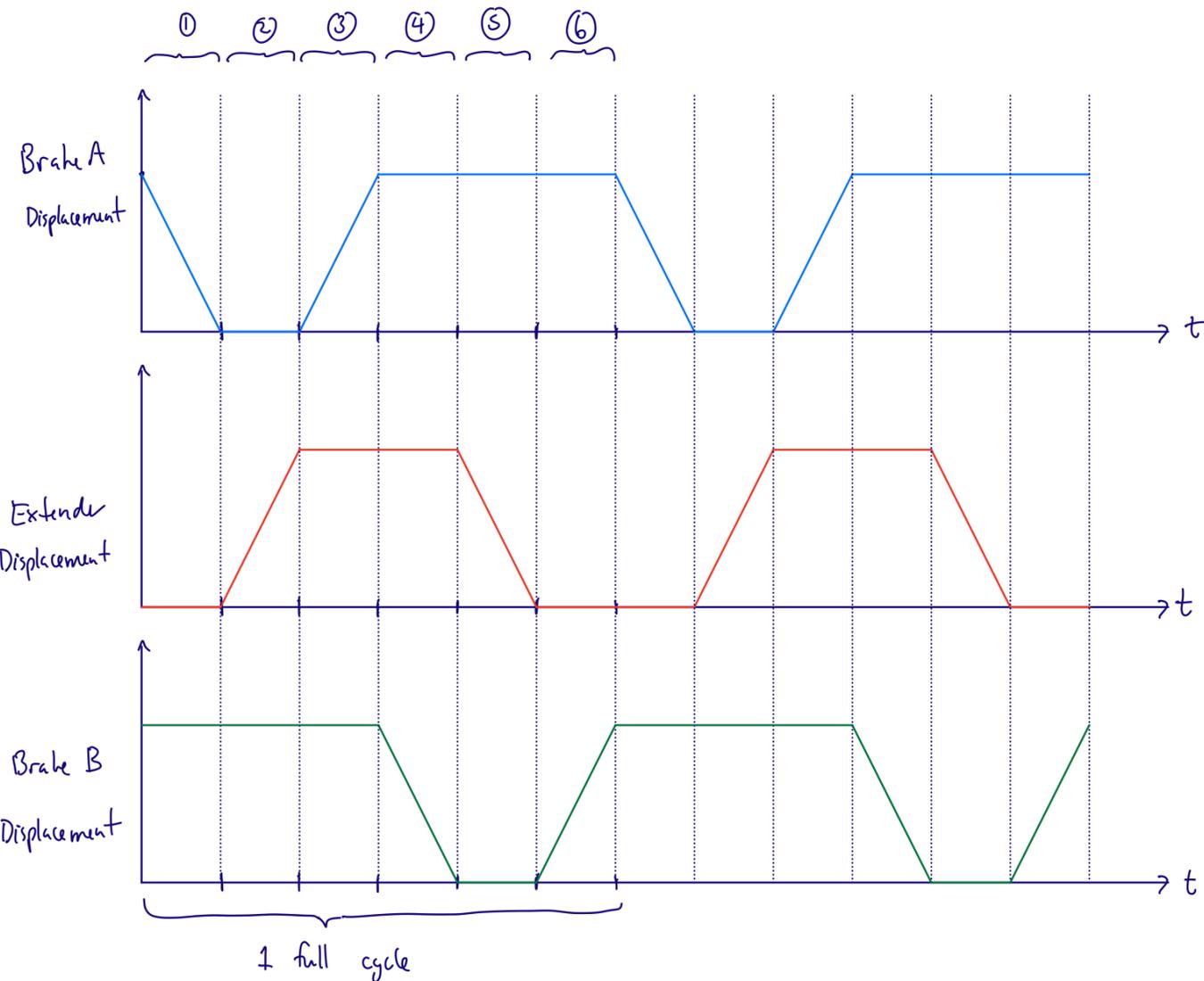
Spring Type	Compression
System of Measurement	Metric
Length	25.5 mm
OD	6.93 mm
ID	5.67 mm
Wire Diameter	0.63 mm
Compressed Length @ Maximum Load	8.9 mm
Maximum Load	2.8 lbs. = 12.455 N
Rate	0.17 lbs./mm = 0.7562 N/mm
Material	Music-Wire Steel
End Type	Closed
Rate Tolerance	-0.01 to 0.01 lbs./mm
OD Tolerance	-0.35 to 0.35 mm
Specifications Met	DIN 17223, DIN 2095, DIN 2098
RoHS	RoHS 3 (2015/863/EU) Compliant
REACH	REACH (EC 1907/2006) (01/19/2021, 211 SVHC) Compliant
DFARS	Specialty Metals COTS-Exempt
Country of Origin	United States
USMCA Qualifying	No
Schedule B	732020.5000
ECCN	EAR99

Inchworm Background

- Inchworm actuator consists of 3 individual stack actuators
 - (Brake A, Brake B, and Extender)
- Frequency-leveraged actuator allows for much larger displacements while still maintaining high output force of piezoelectric stack



Inchworm Background



Cycle period:

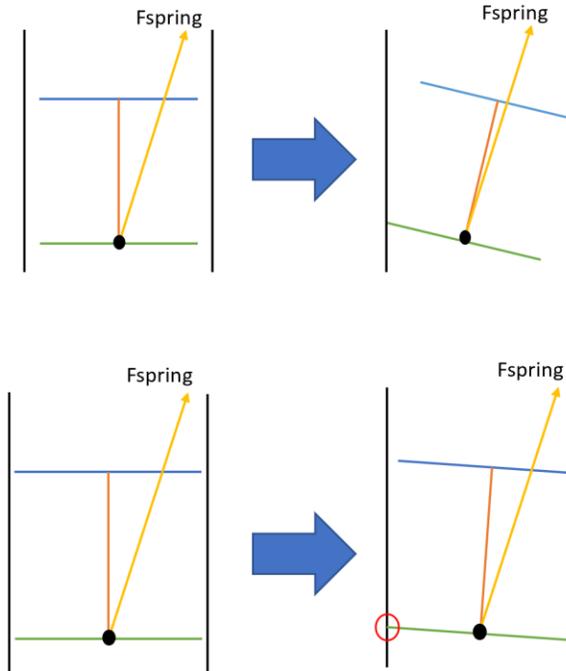
$$T = 2t_e + 4t_b$$

Average Actuation Speed:

$$V_{avg} = \frac{\Delta l_{extender, per\ cycle}}{T}$$

Assumptions for the Brake Design

- The actuator will move within a tube/bore, this provides many advantages, and we will assume that the brakes will only need to contract at least $3\ \mu\text{m}$ to disengage from the walls of the bore ($BORE_c = 3\ \mu\text{m}$).
 - Precision bores can be achieved with high dimensional tolerances, and smooth surface finishes (much better than $3\ \mu\text{m}$, such as wire EDM).
 - Also, having a smaller gap between the actuator and the tube walls will prevent inadvertent damage to the actuator, as shown in the diagram.



Big Gap:

Moment can lock mechanism and may even break piezo actuator.

Small Gap:

Lower normal forces at contact points means that there is higher change that the actuator slides.

Brake Friction and Braking Force

- We know we must apply the following frictional force to the brake...

$$F_f = F_{cable} = \mathbf{166.939\ N}$$

Where,

$$F_f = \mu_{static} \times F_{brake} \quad \text{OR} \quad F_{brake} = \frac{F_{cable}}{\mu_{static}}$$

- So we want to find a high friction coefficient to reduce the needs of the brake.
 - From EngineersEdge we find that steel-on-steel has a static coefficient of 0.8

$$\therefore F_{brake} = 1.25 \times F_{cable} = \mathbf{208.674\ N}$$

Brake Calculator

- Since we want to maximize work, we will have to derive a work function for a stack actuator given our design parameters. This function can be derived from the blocked force and free strain expression. This is shown in the diagram.

$$\delta_o = \frac{d_{33}L_s}{t} \times V$$

$$f_{bl} = \frac{d_{33}A}{S_{33}^E t} \times V$$

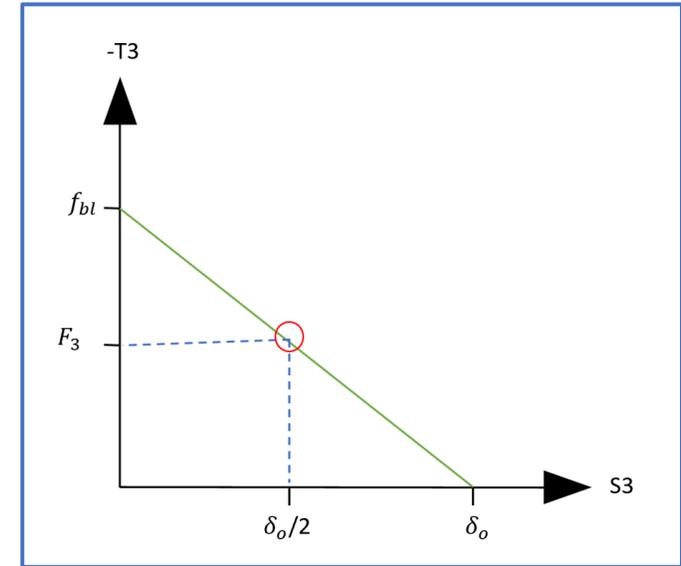
- Combining these produces the following...

$$F_3 = \frac{d_{33}A}{2 \times S_{33}^E t} \times V$$

$$\frac{\delta_o}{2} = \frac{d_{33}L_s V}{2 \times t} = \frac{d_{33}nV}{2} \text{ where, } n = \frac{L_s}{t}$$

At maximum work:

$$F_3 = \left(-\frac{f_{bl}}{\delta_o}\right) \left(\frac{\delta_o}{2}\right) + f_{bl} = \frac{f_{bl}}{2}$$



Brake Calculator

- We can use the previous equations to identify a solution space for each piezo material, which can be applied to the brake design.
- $F_{brake} \leq F_3 = \frac{d_{33}A}{2 \times S_{33}^E t} \times V \rightarrow 3 \text{ variable table}$
- $BORE_c \leq \frac{\delta_0}{2} = \frac{d_{33}L_s V}{2 \times t} = \frac{d_{33}nV}{2} \rightarrow 2 \text{ variable table}$

Brake Calculator

- $F_{brake} \leq F_3 = \frac{d_{33}A}{2 \times S_{33}^E t} \times V \rightarrow 3 \text{ variable table}$

- $BORE_c \leq \frac{\delta_0}{2} = \frac{d_{33}L_s V}{2 \times t} = \frac{d_{33}nV}{2} \rightarrow 2 \text{ variable table}$

APC 856		For A (m2): 5.63E-05 (7.5mm sides)					FORCE TABLE (N):																			
		Volts (V):																								
		150	152	154	156	158	160	162	164	166	168	170	172	174	176	178	180	182	184	186	188	190	192	194	196	198
	1.00E-04	1.54E+03	1.56E+03	1.58E+03	1.60E+03	1.62E+03	1.64E+03	1.66E+03	1.68E+03	1.70E+03	1.72E+03	1.74E+03	1.76E+03	1.78E+03	1.81E+03	1.83E+03	1.85E+03	1.87E+03	1.89E+03	1.91E+03	1.93E+03	1.95E+03	1.97E+03	1.99E+03	2.01E+03	2.03E+03
	2.00E-04	7.69E+02	7.80E+02	7.90E+02	8.00E+02	8.10E+02	8.21E+02	8.31E+02	8.41E+02	8.51E+02	8.62E+02	8.72E+02	8.82E+02	8.92E+02	9.03E+02	9.13E+02	9.23E+02	9.33E+02	9.44E+02	9.54E+02	9.64E+02	9.74E+02	9.85E+02	9.95E+02	1.01E+03	1.02E+03
t (m):	3.00E-04	5.13E+02	5.20E+02	5.27E+02	5.33E+02	5.40E+02	5.47E+02	5.54E+02	5.61E+02	5.68E+02	5.74E+02	5.81E+02	5.88E+02	5.95E+02	6.02E+02	6.09E+02	6.15E+02	6.22E+02	6.29E+02	6.36E+02	6.43E+02	6.50E+02	6.56E+02	6.63E+02	6.70E+02	6.77E+02
	4.00E-04	3.85E+02	3.90E+02	3.95E+02	4.00E+02	4.05E+02	4.10E+02	4.15E+02	4.21E+02	4.26E+02	4.31E+02	4.36E+02	4.41E+02	4.46E+02	4.51E+02	4.56E+02	4.62E+02	4.67E+02	4.72E+02	4.77E+02	4.82E+02	4.87E+02	4.92E+02	4.97E+02	5.03E+02	5.08E+02
	5.00E-04	3.08E+02	3.12E+02	3.16E+02	3.20E+02	3.24E+02	3.28E+02	3.32E+02	3.36E+02	3.41E+02	3.45E+02	3.49E+02	3.53E+02	3.57E+02	3.61E+02	3.65E+02	3.69E+02	3.73E+02	3.77E+02	3.82E+02	3.86E+02	3.90E+02	3.94E+02	3.98E+02	4.02E+02	4.06E+02
	6.00E-04	2.56E+02	2.60E+02	2.63E+02	2.67E+02	2.70E+02	2.74E+02	2.77E+02	2.80E+02	2.84E+02	2.87E+02	2.91E+02	2.94E+02	2.97E+02	3.01E+02	3.04E+02	3.08E+02	3.11E+02	3.15E+02	3.18E+02	3.21E+02	3.25E+02	3.28E+02	3.32E+02	3.35E+02	3.38E+02
	7.00E-04	2.20E+02	2.23E+02	2.26E+02	2.29E+02	2.32E+02	2.34E+02	2.37E+02	2.40E+02	2.43E+02	2.46E+02	2.49E+02	2.52E+02	2.55E+02	2.58E+02	2.61E+02	2.64E+02	2.67E+02	2.70E+02	2.73E+02	2.75E+02	2.78E+02	2.81E+02	2.84E+02	2.87E+02	2.90E+02
	8.00E-04	1.92E+02	1.95E+02	1.97E+02	2.00E+02	2.03E+02	2.05E+02	2.08E+02	2.10E+02	2.13E+02	2.15E+02	2.18E+02	2.21E+02	2.23E+02	2.26E+02	2.28E+02	2.31E+02	2.33E+02	2.36E+02	2.38E+02	2.41E+02	2.44E+02	2.46E+02	2.49E+02	2.51E+02	2.54E+02
	9.00E-04	1.71E+02	1.73E+02	1.76E+02	1.78E+02	1.80E+02	1.82E+02	1.85E+02	1.87E+02	1.89E+02	1.91E+02	1.94E+02	1.96E+02	1.98E+02	2.01E+02	2.03E+02	2.05E+02	2.07E+02	2.10E+02	2.12E+02	2.14E+02	2.17E+02	2.19E+02	2.21E+02	2.23E+02	2.26E+02
	1.00E-03	1.54E+02	1.56E+02	1.58E+02	1.60E+02	1.62E+02	1.64E+02	1.66E+02	1.68E+02	1.70E+02	1.72E+02	1.74E+02	1.76E+02	1.78E+02	1.81E+02	1.83E+02	1.85E+02	1.87E+02	1.89E+02	1.91E+02	1.93E+02	1.95E+02	1.97E+02	1.99E+02	2.01E+02	2.03E+02
		For n (L_s/t) 52					d_o/2 TABLE (m):																			
		Volts (V):																								
L_s (m):	t (m):	150	152	154	156	158	160	162	164	166	168	170	172	174	176	178	180	182	184	186	188	190	192	194	196	198
5.20E-03	1.00E-04	2.42E-06	2.45E-06	2.48E-06	2.51E-06	2.55E-06	2.58E-06	2.61E-06	2.64E-06	2.68E-06	2.71E-06	2.74E-06	2.77E-06	2.80E-06	2.84E-06	2.87E-06	2.90E-06	2.93E-06	2.97E-06	3.00E-06	3.03E-06	3.06E-06	3.10E-06	3.13E-06	3.16E-06	3.19E-06
1.04E-02	2.00E-04	2.42E-06	2.45E-06	2.48E-06	2.51E-06	2.55E-06	2.58E-06	2.61E-06	2.64E-06	2.68E-06	2.71E-06	2.74E-06	2.77E-06	2.80E-06	2.84E-06	2.87E-06	2.90E-06	2.93E-06	2.97E-06	3.00E-06	3.03E-06	3.06E-06	3.10E-06	3.13E-06	3.16E-06	3.19E-06
1.56E-02	3.00E-04	2.42E-06	2.45E-06	2.48E-06	2.51E-06	2.55E-06	2.58E-06	2.61E-06	2.64E-06	2.68E-06	2.71E-06	2.74E-06	2.77E-06	2.80E-06	2.84E-06	2.87E-06	2.90E-06	2.93E-06	2.97E-06	3.00E-06	3.03E-06	3.06E-06	3.10E-06	3.13E-06	3.16E-06	3.19E-06
2.08E-02	4.00E-04	2.42E-06	2.45E-06	2.48E-06	2.51E-06	2.55E-06	2.58E-06	2.61E-06	2.64E-06	2.68E-06	2.71E-06	2.74E-06	2.77E-06	2.80E-06	2.84E-06	2.87E-06	2.90E-06	2.93E-06	2.97E-06	3.00E-06	3.03E-06	3.06E-06	3.10E-06	3.13E-06	3.16E-06	3.19E-06
2.60E-02	5.00E-04	2.42E-06	2.45E-06	2.48E-06	2.51E-06	2.55E-06	2.58E-06	2.61E-06	2.64E-06	2.68E-06	2.71E-06	2.74E-06	2.77E-06	2.80E-06	2.84E-06	2.87E-06	2.90E-06	2.93E-06	2.97E-06	3.00E-06	3.03E-06	3.06E-06	3.10E-06	3.13E-06	3.16E-06	3.19E-06
3.12E-02	6.00E-04	2.42E-06	2.45E-06	2.48E-06	2.51E-06	2.55E-06	2.58E-06	2.61E-06	2.64E-06	2.68E-06	2.71E-06	2.74E-06	2.77E-06	2.80E-06	2.84E-06	2.87E-06	2.90E-06	2.93E-06	2.97E-06	3.00E-06	3.03E-06	3.06E-06	3.10E-06	3.13E-06	3.16E-06	3.19E-06
3.64E-02	7.00E-04	2.42E-06	2.45E-06	2.48E-06	2.51E-06	2.55E-06	2.58E-06	2.61E-06	2.64E-06	2.68E-06	2.71E-06	2.74E-06	2.77E-06	2.80E-06	2.84E-06	2.87E-06	2.90E-06	2.93E-06	2.97E-06	3.00E-06	3.03E-06	3.06E-06	3.10E-06	3.13E-06	3.16E-06	3.19E-06
4.16E-02	8.00E-04	2.42E-06	2.45E-06	2.48E-06	2.51E-06	2.55E-06	2.58E-06	2.61E-06	2.64E-06	2.68E-06	2.71E-06	2.74E-06	2.77E-06	2.80E-06	2.84E-06	2.87E-06	2.90E-06	2.93E-06	2.97E-06	3.00E-06	3.03E-06	3.06E-06	3.10E-06	3.13E-06	3.16E-06	3.19E-06
4.68E-02	9.00E-04	2.42E-06	2.45E-06	2.48E-06	2.51E-06	2.55E-06	2.58E-06	2.61E-06	2.64E-06	2.68E-06	2.71E-06	2.74E-06	2.77E-06	2.80E-06	2.84E-06	2.87E-06	2.90E-06	2.93E-06	2.97E-06	3.00E-06	3.03E-06	3.06E-06	3.10E-06	3.13E-06	3.16E-06	3.19E-06
5.20E-02	1.00E-03	2.42E-06	2.45E-06	2.48E-06	2.51E-06	2.55E-06	2.58E-06	2.61E-06	2.64E-06	2.68E-06	2.71E-06	2.74E-06	2.77E-06	2.80E-06	2.84E-06	2.87E-06	2.90E-06	2.93E-06	2.97E-06	3.00E-06	3.03E-06	3.06E-06	3.10E-06	3.13E-06	3.16E-06	3.19E-06

Extender Calculator

- Similar to the brake design, we will design the extension member to maximize work in the 3 direction, and we will use our blocked stress – free strain relationship to achieve this.

- We know the following...

$$\frac{f_{bl}}{2} = F_{unk} = F_{cable}$$

$$\frac{\delta_o}{2} = (\text{step size})$$

- Combined this with the work function and we get...

$$\text{side length} = \sqrt{A} = \sqrt{\frac{2 \times F_{cable} S_{33}^E t}{d_{33} V}}$$

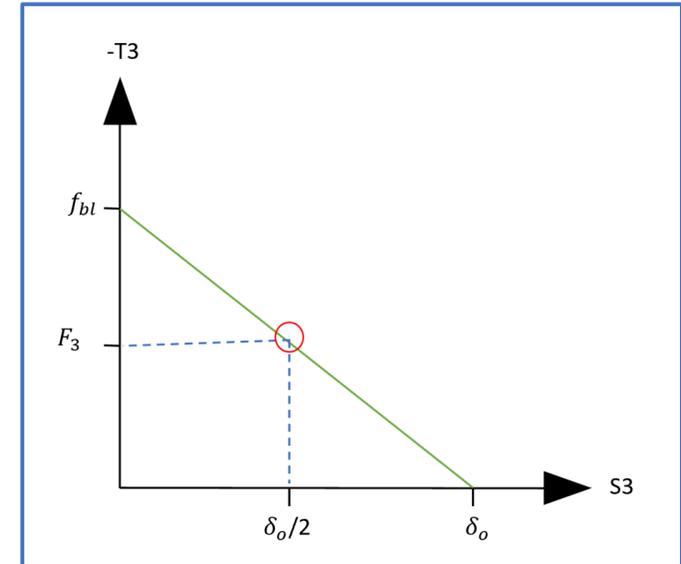
$$\text{step size} = \frac{\delta_o}{2} = \frac{d_{33} L_s}{2 \times t} \times V$$

$$\delta_o = \frac{d_{33} L_s}{t} \times V$$

$$f_{bl} = \frac{d_{33} A}{S_{33}^E t} \times V$$

At maximum work:

$$F_3 = \left(-\frac{f_{bl}}{\delta_o} \right) \left(\frac{\delta_o}{2} \right) + f_{bl} = \frac{f_{bl}}{2}$$



Extender Calculator

- Using the equations we just derived, we generate a solution space for the extension member of the inchworm actuator, by characterizing each piezo material.

- *side length* = $\sqrt{A} = \sqrt{\frac{2 \times F_{cable} S_{33}^E t}{d_{33} V}}$ → 2 variable table

- *step size* = $\frac{\delta_o}{2} = \frac{d_{33} L_s V}{2 \times t} = \frac{d_{33} n V}{2}$ → 2 variable table

Extender Calculator

- side length = $\sqrt{A} = \sqrt{\frac{2 \times F_{cable} S_{33}^E t}{d_{33} V}} \rightarrow 2 \text{ variable table}$
- step size = $\frac{\delta_o}{2} = \frac{d_{33} L_s V}{2 \times t} = \frac{d_{33} n V}{2} \rightarrow 2 \text{ variable table}$

APC 856		SIDE LENGTH [sqrt(A)] TABLE (m):																							
		Volts (V):																							
t (m):	150	152	154	156	158	160	162	164	166	168	170	172	174	176	178	180	182	184	186	188	190	192	194	196	198
1.00E-04	2.47E-03	2.45E-03	2.44E-03	2.42E-03	2.41E-03	2.39E-03	2.38E-03	2.36E-03	2.35E-03	2.33E-03	2.32E-03	2.31E-03	2.29E-03	2.28E-03	2.27E-03	2.26E-03	2.24E-03	2.23E-03	2.22E-03	2.21E-03	2.20E-03	2.18E-03	2.17E-03	2.16E-03	2.15E-03
1.10E-04	2.59E-03	2.57E-03	2.56E-03	2.54E-03	2.52E-03	2.51E-03	2.49E-03	2.48E-03	2.46E-03	2.45E-03	2.43E-03	2.42E-03	2.41E-03	2.39E-03	2.38E-03	2.37E-03	2.35E-03	2.34E-03	2.33E-03	2.31E-03	2.30E-03	2.29E-03	2.28E-03	2.27E-03	2.26E-03
1.20E-04	2.71E-03	2.69E-03	2.67E-03	2.65E-03	2.64E-03	2.62E-03	2.60E-03	2.59E-03	2.57E-03	2.56E-03	2.54E-03	2.53E-03	2.51E-03	2.50E-03	2.48E-03	2.47E-03	2.46E-03	2.44E-03	2.43E-03	2.42E-03	2.40E-03	2.39E-03	2.38E-03	2.37E-03	2.36E-03
1.30E-04	2.82E-03	2.80E-03	2.78E-03	2.76E-03	2.74E-03	2.73E-03	2.71E-03	2.69E-03	2.68E-03	2.66E-03	2.65E-03	2.63E-03	2.62E-03	2.60E-03	2.59E-03	2.57E-03	2.56E-03	2.54E-03	2.53E-03	2.52E-03	2.50E-03	2.49E-03	2.48E-03	2.46E-03	2.45E-03
1.40E-04	2.92E-03	2.90E-03	2.88E-03	2.87E-03	2.85E-03	2.83E-03	2.81E-03	2.80E-03	2.78E-03	2.76E-03	2.75E-03	2.73E-03	2.71E-03	2.70E-03	2.68E-03	2.67E-03	2.65E-03	2.64E-03	2.63E-03	2.61E-03	2.60E-03	2.58E-03	2.57E-03	2.56E-03	2.54E-03
1.50E-04	3.03E-03	3.01E-03	2.99E-03	2.97E-03	2.95E-03	2.93E-03	2.91E-03	2.89E-03	2.88E-03	2.86E-03	2.84E-03	2.83E-03	2.81E-03	2.79E-03	2.78E-03	2.76E-03	2.75E-03	2.73E-03	2.72E-03	2.70E-03	2.69E-03	2.67E-03	2.66E-03	2.65E-03	2.63E-03
1.60E-04	3.12E-03	3.10E-03	3.08E-03	3.06E-03	3.04E-03	3.03E-03	3.01E-03	2.99E-03	2.97E-03	2.95E-03	2.94E-03	2.92E-03	2.90E-03	2.88E-03	2.87E-03	2.85E-03	2.84E-03	2.82E-03	2.81E-03	2.79E-03	2.78E-03	2.76E-03	2.75E-03	2.73E-03	2.72E-03
1.70E-04	3.22E-03	3.20E-03	3.18E-03	3.16E-03	3.14E-03	3.12E-03	3.10E-03	3.08E-03	3.06E-03	3.04E-03	3.03E-03	3.01E-03	2.99E-03	2.97E-03	2.96E-03	2.94E-03	2.92E-03	2.91E-03	2.89E-03	2.88E-03	2.86E-03	2.85E-03	2.83E-03	2.82E-03	2.80E-03
1.80E-04	3.31E-03	3.29E-03	3.27E-03	3.25E-03	3.23E-03	3.21E-03	3.19E-03	3.17E-03	3.15E-03	3.13E-03	3.11E-03	3.10E-03	3.08E-03	3.06E-03	3.04E-03	3.03E-03	3.01E-03	2.99E-03	2.98E-03	2.96E-03	2.94E-03	2.93E-03	2.91E-03	2.90E-03	2.88E-03
1.90E-04	3.41E-03	3.38E-03	3.36E-03	3.34E-03	3.32E-03	3.30E-03	3.28E-03	3.26E-03	3.24E-03	3.22E-03	3.20E-03	3.18E-03	3.16E-03	3.14E-03	3.13E-03	3.11E-03	3.09E-03	3.07E-03	3.06E-03	3.04E-03	3.03E-03	3.01E-03	2.99E-03	2.98E-03	2.96E-03
2.00E-04	3.49E-03	3.47E-03	3.45E-03	3.43E-03	3.40E-03	3.38E-03	3.36E-03	3.34E-03	3.32E-03	3.30E-03	3.28E-03	3.26E-03	3.24E-03	3.23E-03	3.21E-03	3.19E-03	3.17E-03	3.15E-03	3.14E-03	3.12E-03	3.10E-03	3.09E-03	3.07E-03	3.06E-03	3.04E-03
2.10E-04	3.58E-03	3.56E-03	3.53E-03	3.51E-03	3.49E-03	3.47E-03	3.44E-03	3.42E-03	3.40E-03	3.38E-03	3.36E-03	3.34E-03	3.32E-03	3.31E-03	3.29E-03	3.27E-03	3.25E-03	3.23E-03	3.21E-03	3.20E-03	3.18E-03	3.16E-03	3.15E-03	3.13E-03	3.12E-03
2.20E-04	3.66E-03	3.64E-03	3.62E-03	3.59E-03	3.57E-03	3.55E-03	3.53E-03	3.50E-03	3.48E-03	3.46E-03	3.44E-03	3.42E-03	3.40E-03	3.38E-03	3.36E-03	3.35E-03	3.33E-03	3.31E-03	3.29E-03	3.27E-03	3.26E-03	3.24E-03	3.22E-03	3.21E-03	3.19E-03
2.30E-04	3.75E-03	3.72E-03	3.70E-03	3.67E-03	3.65E-03	3.63E-03	3.61E-03	3.58E-03	3.56E-03	3.54E-03	3.52E-03	3.50E-03	3.48E-03	3.46E-03	3.44E-03	3.42E-03	3.40E-03	3.38E-03	3.36E-03	3.35E-03	3.33E-03	3.31E-03	3.29E-03	3.28E-03	3.26E-03
2.40E-04	3.83E-03	3.80E-03	3.78E-03	3.75E-03	3.73E-03	3.71E-03	3.68E-03	3.66E-03	3.64E-03	3.62E-03	3.60E-03	3.57E-03	3.55E-03	3.53E-03	3.51E-03	3.49E-03	3.47E-03	3.46E-03	3.44E-03	3.42E-03	3.40E-03	3.38E-03	3.37E-03	3.35E-03	3.33E-03
2.50E-04	3.91E-03	3.88E-03	3.86E-03	3.83E-03	3.81E-03	3.78E-03	3.76E-03	3.74E-03	3.71E-03	3.69E-03	3.67E-03	3.65E-03	3.63E-03	3.61E-03	3.59E-03	3.57E-03	3.55E-03	3.53E-03	3.51E-03	3.49E-03	3.47E-03	3.45E-03	3.43E-03	3.42E-03	3.40E-03

can be changed ->		For n (L_s/t):		[d_0/2] (step distance) TABLE (m):																							
		83		Volts (V):																							
L_s (m):	t (m):	150	152	154	156	158	160	162	164	166	168	170	172	174	176	178	180	182	184	186	188	190	192	194	196	198	
8.30E-03	1.00E-04	3.86E-06	3.91E-06	3.96E-06	4.01E-06	4.07E-06	4.12E-06	4.17E-06	4.22E-06	4.27E-06	4.32E-06	4.37E-06	4.43E-06	4.48E-06	4.53E-06	4.58E-06	4.63E-06	4.68E-06	4.73E-06	4.79E-06	4.84E-06	4.89E-06	4.94E-06	4.99E-06	5.04E-06	5.09E-06	
9.13E-03	1.10E-04	3.86E-06	3.91E-06	3.96E-06	4.01E-06	4.07E-06	4.12E-06	4.17E-06	4.22E-06	4.27E-06	4.32E-06	4.37E-06	4.43E-06	4.48E-06	4.53E-06	4.58E-06	4.63E-06	4.68E-06	4.73E-06	4.79E-06	4.84E-06	4.89E-06	4.94E-06	4.99E-06	5.04E-06	5.09E-06	
9.96E-03	1.20E-04	3.86E-06	3.91E-06	3.96E-06	4.01E-06	4.07E-06	4.12E-06	4.17E-06	4.22E-06	4.27E-06	4.32E-06	4.37E-06	4.43E-06	4.48E-06	4.53E-06	4.58E-06	4.63E-06	4.68E-06	4.73E-06	4.79E-06	4.84E-06	4.89E-06	4.94E-06	4.99E-06	5.04E-06	5.09E-06	
1.08E-02	1.30E-04	3.86E-06	3.91E-06	3.96E-06	4.01E-06	4.07E-06	4.12E-06	4.17E-06	4.22E-06	4.27E-06	4.32E-06	4.37E-06	4.43E-06	4.48E-06	4.53E-06	4.58E-06	4.63E-06	4.68E-06	4.73E-06	4.79E-06	4.84E-06	4.89E-06	4.94E-06	4.99E-06	5.04E-06	5.09E-06	
1.16E-02	1.40E-04	3.86E-06	3.91E-06	3.96E-06	4.01E-06	4.07E-06	4.12E-06	4.17E-06	4.22E-06	4.27E-06	4.32E-06	4.37E-06	4.43E-06	4.48E-06	4.53E-06	4.58E-06	4.63E-06	4.68E-06	4.73E-06	4.79E-06	4.84E-06	4.89E-06	4.94E-06	4.99E-06	5.04E-06	5.09E-06	
1.25E-02	1.50E-04	3.86E-06	3.91E-06	3.96E-06	4.01E-06	4.07E-06	4.12E-06	4.17E-06	4.22E-06	4.27E-06	4.32E-06	4.37E-06	4.43E-06	4.48E-06	4.53E-06	4.58E-06	4.63E-06	4.68E-06	4.73E-06	4.79E-06	4.84E-06	4.89E-06	4.94E-06	4.99E-06	5.04E-06	5.09E-06	
1.33E-02	1.60E-04	3.86E-06	3.91E-06	3.96E-06	4.01E-06	4.07E-06	4.12E-06	4.17E-06	4.22E-06	4.27E-06	4.32E-06	4.37E-06	4.43E-06	4.48E-06	4.53E-06	4.58E-06	4.63E-06	4.68E-06	4.73E-06	4.79E-06	4.84E-06	4.89E-06	4.94E-06	4.99E-06	5.04E-06	5.09E-06	
1.41E-02	1.70E-04	3.86E-06	3.91E-06	3.96E-06	4.01E-06	4.07E-06	4.12E-06	4.17E-06	4.22E-06	4.27E-06	4.32E-06	4.37E-06	4.43E-06	4.48E-06	4.53E-06	4.58E-06	4.63E-06	4.68E-06	4.73E-06	4.79E-06	4.84E-06	4.89E-06	4.94E-06	4.99E-06	5.04E-06	5.09E-06	
1.49E-02	1.80E-04	3.86E-06	3.91E-06	3.96E-06	4.01E-06	4.07E-06	4.12E-06	4.17E-06	4.22E-06	4.27E-06	4.32E-06	4.37E-06	4.43E-06	4.48E-06	4.53E-06	4.58E-06	4.63E-06	4.68E-06	4.73E-06	4.79E-06	4.84E-06	4.89E-06	4.94E-06	4.99E-06	5.04E-06	5.09E-06	
1.58E-02	1.90E-04	3.86E-06	3.91E-06	3.96E-06	4.01E-06	4.07E-06	4.12E-06	4.17E-06	4.22E-06	4.27E-06	4.32E-06	4.37E-06	4.43E-06	4.48E-06	4.53E-06	4.58E-06	4.63E-06	4.68E-06	4.73E-06	4.79E-06	4.84E-06	4.89E-06	4.94E-06	4.99E-06	5.04E-06	5.09E-06	
1.66E-02	2.00E-04	3.86E-06	3.91E-06	3.96E-06	4.01E-06	4.07E-06	4.12E-06	4.17E-06	4.22E-06	4.27E-06	4.32E-06	4.37E-06	4.43E-06	4.48E-06	4.53E-06	4.58E-06	4.63E-06	4.68E-06	4.73E-06	4.79E-06	4.84E-06	4.89E-06	4.94E-06	4.99E-06	5.04E-06	5.09E-06	
1.74E-02	2.10E-04	3.86E-06	3.91E-06	3.96E-06	4.01E-06	4.07E-06	4.12E-06	4.17E-06	4.22E-06	4.27E-06	4.32E-06	4.37E-06	4.43E-06	4.48E-06	4.53E-06	4.58E-06	4.63E-06	4.68E-06	4.73E-06	4.79E-06	4.84E-06	4.89E-06	4.94E-06	4.99E-06	5.04E-06	5.09E-06	
1.83E-02	2.20E-04	3.86E-06	3.91E-06	3.96E-06	4.01E-06	4.07E-06	4.12E-06	4.17E-06	4.22E-06	4.27E-06	4.32E-06	4.37E-06	4.43E-06	4.48E-06	4.53E-06	4.58E-06	4.63E-06	4.68E-06	4.73E-06	4.79E-06	4.84E-06	4.89E-06	4.94E-06	4.99E-06	5.04E-06	5.09E-06	
1.91E-02	2.30E-04	3.86E-06	3.91E-06	3.96E-06	4.01E-06	4.07E-06	4.12E-06	4.17E-06	4.22E-06	4.27E-06	4.32E-06	4.37E-06	4.43E-06	4.48E-06	4.53E-06	4.58E-06	4.63E-06	4.68E-06	4.73E-06	4.79E-06	4.84E-06	4.89E-06	4.94E-06	4.99E-06	5.04E-06	5.09E-06	
1.99E-02	2.40E-04	3.86E-06	3.91E-06	3.96E-06	4.01E-06	4.07E-06	4.12E-06	4.17E-06	4.22E-06	4.27E-06	4.32E-06	4.37E-06	4.43E-06	4.48E-06	4.53E-06	4.58E-06	4.63E-06	4.68E-06	4.73E-06	4.79E-06	4.84E-06	4.89E-06	4.94E-06	4.99E-06	5.04E-06	5.09E-06	
2.08E-02	2.50E-04	3.86E-06	3.91E-06	3.96E-06	4.01E-06	4.07E-06	4.12E-06	4.17E-06	4.22E-06	4.27E-06	4.32E-06	4.37E-06	4.43E-06	4.48E-06	4.53E-06	4.58E-06	4.63E-06	4.68E-06	4.73E-06	4.79E-06	4.84E-06	4.89E-06	4.94E-06	4.99E-06	5.04E-06	5.09E-06	

Inchworm Actuation Speed

Previously defined:

Cycle period:

$$T = 2t_e + 4t_b$$

Average Actuation Speed:

$$V_{avg} = \frac{\Delta l_{extender, per\ cycle}}{T}$$

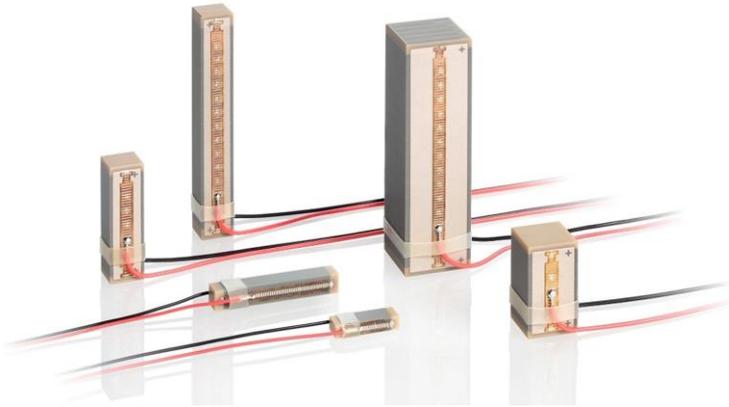
Time for piezo to reach nominal displacement when unloaded (PI Ceramic, n.d.):

$$t_{min} \approx \frac{1}{3f_0}$$

Resonant Frequency (without load) [Hz]

Inchworm Actuation Speed

Illustrative Example for Maximum Actuation Speed



P-882 – P-888 PICMA® Stack Multilayer Piezo Actuators
Image courtesy of PI USA

$$t_e \approx 8.33 \mu s$$

$$t_b \approx 2.47 \mu s$$

$$T = 2t_e + 4t_b = 26.5 \mu s$$

$$V_{avg} = \frac{\Delta l_{extender, per\ cycle}}{T} = \frac{32 \times 10^{-3} \text{ mm}}{26.5 \times 10^{-6} \text{ s}} = 1206 \text{ mm/s!}$$

$$T^{-1} = \frac{1}{26.5 \times 10^{-6} \text{ s}} = 37,700 \text{ Hz (unrealistic)}$$

Actuator	Dimensions [mm]	Nominal Displacement [um]	Blocked Force [N]	Resonant Frequency, f_0 [Hz]
Equivalent piezo for brakes: P-883.11	3 x 3 x 9	6.5	290	135,000
Equivalent piezo for extender: P-885.91	5 x 5 x 36	32	950	40,000

(PI USA, n.d.)

Inchworm Actuation Speed

Illustrative Example for Maximum Actuation Speed (cont'd)

$$t_e \approx 8.33 \mu s$$

$$t_b \approx 2.47 \mu s$$

$$T = 2t_e + 4t_b = 26.5 \mu s$$

$$V_{avg} = \frac{\Delta l_{extender, per\ cycle}}{T} = \frac{32 \times 10^{-3} \text{ mm}}{26.5 \times 10^{-6} \text{ s}} = 1206 \text{ mm/s!}$$

$$T^{-1} = \frac{1}{26.5 \times 10^{-6} \text{ s}} = 37,700 \text{ Hz (unrealistic)}$$

- Instead, we can see that the driving frequency of the actuator (as opposed to the response time of the piezos) will be the limiting factor
- Driving this illustrative actuator at a lower frequency of 275 Hz will allow us to achieve our target speed of 8.73 mm/s

$$V_{avg} = \Delta l_{extender, per\ cycle} \times f_{actuator} = 32 \times 10^{-3} \text{ mm} \times 275 \text{ Hz} = 8.80 \text{ mm/s}$$

Next Steps

- Result from design calculators
 - Material choice for the piezo actuators.
 - Actuator size and configuration.
- Characterize actuator speed against applied force.
- Concluding remarks and feasibility.

Thank You!

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