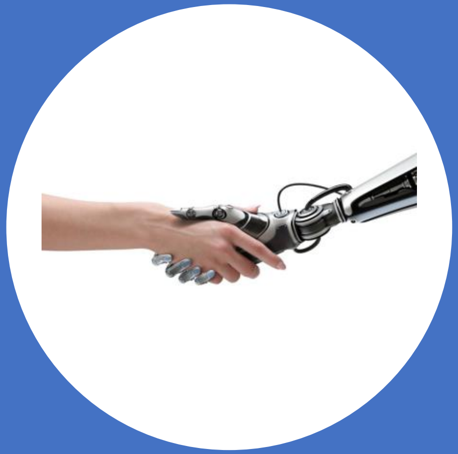


Smart Hand – Presentation 3

By: Adrian, Abdeali, and Luc

Group 1

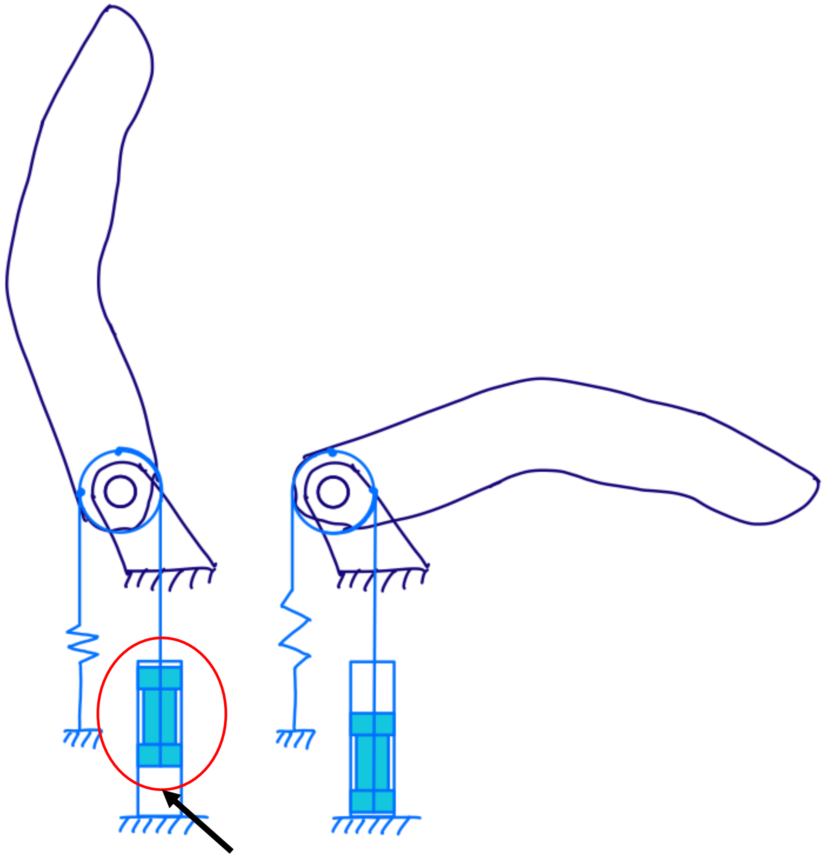
Presentation Overview

- Brief Project Summary
- Piezo Selection Process – Brake and Extender
- Packaging of Inchworm Actuator
- Modeling of Actuation Speed
- High-level Prosthetic Hand Overview
- Comparison and Conclusion
- Q&A

Section 1: Recap

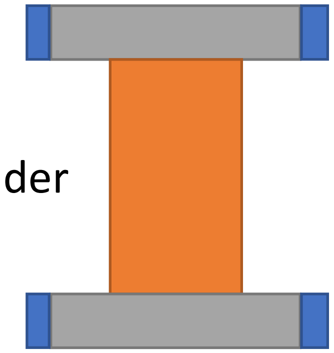
Project Goals:

- Can piezoelectric inchworm actuation address a need for improved prosthetic hands?
- 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



Forward Brake

Extender



Rear Brake

Design Specifications Recap:

Applied force at fingertip of 10 N when fully closed ($\theta = 90\ deg$)

Finger rotational speed of $\dot{\theta} = 100\,\frac{deg}{s}$

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

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

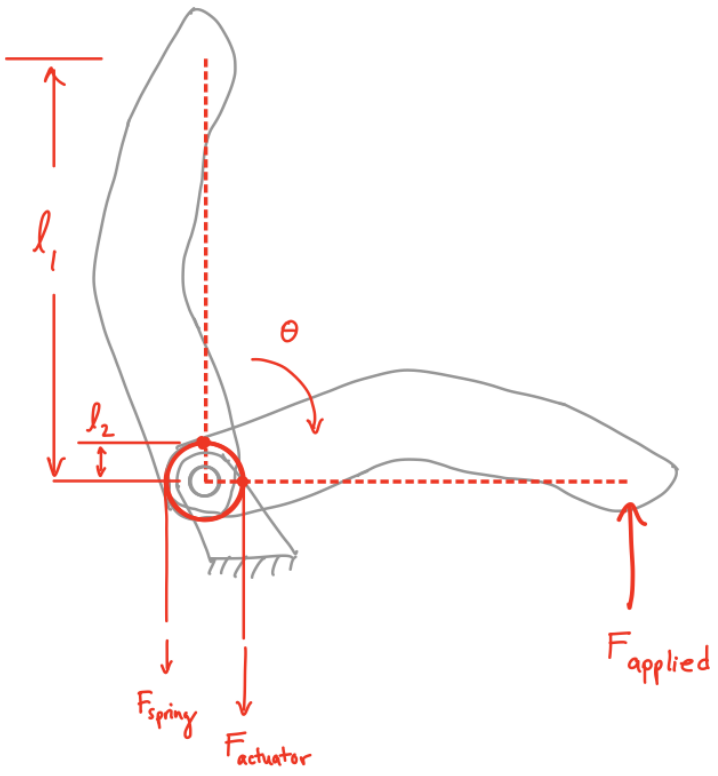
$\Rightarrow \boldsymbol{\Delta l_{actuator} = 7.85\ mm}$

$\Rightarrow \boldsymbol{V_{avg} = 8.73\ mm/s}$

Also, since: $V_{avg} = \Delta l_{extender,\,per\ cycle} \times f_{actuator}$

If we limit $f_{actuator}$ to 300 Hz:

$\Rightarrow \boldsymbol{\Delta l_{extender,\,per\ cycle} = 29.1\ \mu m}$



Section 2:
Piezo Selection

Brake and Extender Calculators

Brake:

- Uses max. work relationship
- $F_{brake} \leq F_3 = \frac{d_{33}A}{2\times S_{33}^E t} \times V \rightarrow 3\ variable\ table$
  - $F_{brake} = 208.674\ N$
- $BORE_c \leq \frac{\delta_0}{2} = \frac{d_{33}L_sV}{2\times t} = \frac{d_{33}nV}{2} \rightarrow 2\ variable\ table$
  - $BORE_c = 3\ \mu m$

Extender:

- Uses max. work relationship
- $side\ length = \sqrt{A} = \sqrt{\frac{2\times F_{cable}S_{33}^E t}{d_{33}V}} \rightarrow 2\ variable\ table$
  - $F_{cable} = 166.939\ N = \frac{f_{bl}}{2}$
- $step\ size = \frac{\delta_o}{2} = \frac{d_{33}L_sV}{2\times t} = \frac{d_{33}nV}{2} \rightarrow 2\ variable\ table$

Brake Calculator – Selection

- $F_{brake} \leq F_3 = \frac{d_{33}A}{2 \times S_{33}^{E} t} \times V \rightarrow 3\ variable\ table$
- $BORE_c \leq \frac{\delta_0}{2} = \frac{d_{33} L_s V}{2 \times t} = \frac{d_{33} n V}{2} \rightarrow 2\ variable\ table$

APC 856

For A (m2): 7.53E-06 (2.75mm sides)

FORCE TABLE (N):

t (m):	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	2.06E+02	2.09E+02	2.11E+02	2.14E+02	2.17E+02	2.20E+02	2.22E+02	2.25E+02	2.28E+02	2.31E+02	2.33E+02	2.36E+02	2.39E+02	2.42E+02	2.44E+02	2.47E+02	2.50E+02	2.53E+02	2.55E+02	2.58E+02	2.61E+02	2.64E+02	**2.66E+02**	2.69E+02	2.72E+02
2.00E-04	1.03E+02	1.04E+02	1.06E+02	1.07E+02	1.08E+02	1.10E+02	1.11E+02	1.13E+02	1.14E+02	1.15E+02	1.17E+02	1.18E+02	1.19E+02	1.21E+02	1.22E+02	1.24E+02	1.25E+02	1.26E+02	1.28E+02	1.29E+02	1.30E+02	1.32E+02	1.33E+02	1.35E+02	1.36E+02
3.00E-04	6.86E+01	6.95E+01	7.05E+01	7.14E+01	7.23E+01	7.32E+01	7.41E+01	7.50E+01	7.59E+01	7.69E+01	7.78E+01	7.87E+01	7.96E+01	8.05E+01	8.14E+01	8.23E+01	8.33E+01	8.42E+01	8.51E+01	8.60E+01	8.69E+01	8.78E+01	8.88E+01	8.97E+01	9.06E+01
4.00E-04	5.15E+01	5.22E+01	5.28E+01	5.35E+01	5.42E+01	5.49E+01	5.56E+01	5.63E+01	5.70E+01	5.76E+01	5.83E+01	5.90E+01	5.97E+01	6.04E+01	6.11E+01	6.18E+01	6.24E+01	6.31E+01	6.38E+01	6.45E+01	6.52E+01	6.59E+01	6.66E+01	6.73E+01	6.79E+01
5.00E-04	4.12E+01	4.17E+01	4.23E+01	4.28E+01	4.34E+01	4.39E+01	4.45E+01	4.50E+01	4.56E+01	4.61E+01	4.67E+01	4.72E+01	4.78E+01	4.83E+01	4.89E+01	4.94E+01	5.00E+01	5.05E+01	5.11E+01	5.16E+01	5.22E+01	5.27E+01	5.33E+01	5.38E+01	5.44E+01
6.00E-04	3.43E+01	3.48E+01	3.52E+01	3.57E+01	3.61E+01	3.66E+01	3.71E+01	3.75E+01	3.80E+01	3.84E+01	3.89E+01	3.93E+01	3.98E+01	4.03E+01	4.07E+01	4.12E+01	4.16E+01	4.21E+01	4.25E+01	4.30E+01	4.35E+01	4.39E+01	4.44E+01	4.48E+01	4.53E+01
7.00E-04	2.94E+01	2.98E+01	3.02E+01	3.06E+01	3.10E+01	3.14E+01	3.18E+01	3.22E+01	3.25E+01	3.29E+01	3.33E+01	3.37E+01	3.41E+01	3.45E+01	3.49E+01	3.53E+01	3.57E+01	3.61E+01	3.65E+01	3.69E+01	3.73E+01	3.76E+01	3.80E+01	3.84E+01	3.88E+01
8.00E-04	2.57E+01	2.61E+01	2.64E+01	2.68E+01	2.71E+01	2.74E+01	2.78E+01	2.81E+01	2.85E+01	2.88E+01	2.92E+01	2.95E+01	2.99E+01	3.02E+01	3.05E+01	3.09E+01	3.12E+01	3.16E+01	3.19E+01	3.23E+01	3.26E+01	3.29E+01	3.33E+01	3.36E+01	3.40E+01
9.00E-04	2.29E+01	2.32E+01	2.35E+01	2.38E+01	2.41E+01	2.44E+01	2.47E+01	2.50E+01	2.53E+01	2.56E+01	2.59E+01	2.62E+01	2.65E+01	2.68E+01	2.71E+01	2.74E+01	2.78E+01	2.81E+01	2.84E+01	2.87E+01	2.90E+01	2.93E+01	2.96E+01	2.99E+01	3.02E+01
1.00E-03	2.06E+01	2.09E+01	2.11E+01	2.14E+01	2.17E+01	2.20E+01	2.22E+01	2.25E+01	2.28E+01	2.31E+01	2.33E+01	2.36E+01	2.39E+01	2.42E+01	2.44E+01	2.47E+01	2.50E+01	2.53E+01	2.55E+01	2.58E+01	2.61E+01	2.64E+01	2.66E+01	2.69E+01	2.72E+01

For n (L_s/t): 50

d_o/2 TABLE (m):

L_s (m):	t (m):	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
5.00E-03	1.00E-04	2.33E-06	2.36E-06	2.39E-06	2.42E-06	2.45E-06	2.48E-06	2.51E-06	2.54E-06	2.57E-06	2.60E-06	2.64E-06	2.67E-06	2.70E-06	2.73E-06	2.76E-06	2.79E-06	2.82E-06	2.85E-06	2.88E-06	2.91E-06	2.95E-06	2.98E-06	**3.01E-06**	3.04E-06	3.07E-06
1.00E-02	2.00E-04	2.33E-06	2.36E-06	2.39E-06	2.42E-06	2.45E-06	2.48E-06	2.51E-06	2.54E-06	2.57E-06	2.60E-06	2.64E-06	2.67E-06	2.70E-06	2.73E-06	2.76E-06	2.79E-06	2.82E-06	2.85E-06	2.88E-06	2.91E-06	2.95E-06	2.98E-06	3.01E-06	3.04E-06	3.07E-06
1.50E-02	3.00E-04	2.33E-06	2.36E-06	2.39E-06	2.42E-06	2.45E-06	2.48E-06	2.51E-06	2.54E-06	2.57E-06	2.60E-06	2.64E-06	2.67E-06	2.70E-06	2.73E-06	2.76E-06	2.79E-06	2.82E-06	2.85E-06	2.88E-06	2.91E-06	2.95E-06	2.98E-06	3.01E-06	3.04E-06	3.07E-06
2.00E-02	4.00E-04	2.33E-06	2.36E-06	2.39E-06	2.42E-06	2.45E-06	2.48E-06	2.51E-06	2.54E-06	2.57E-06	2.60E-06	2.64E-06	2.67E-06	2.70E-06	2.73E-06	2.76E-06	2.79E-06	2.82E-06	2.85E-06	2.88E-06	2.91E-06	2.95E-06	2.98E-06	3.01E-06	3.04E-06	3.07E-06
2.50E-02	5.00E-04	2.33E-06	2.36E-06	2.39E-06	2.42E-06	2.45E-06	2.48E-06	2.51E-06	2.54E-06	2.57E-06	2.60E-06	2.64E-06	2.67E-06	2.70E-06	2.73E-06	2.76E-06	2.79E-06	2.82E-06	2.85E-06	2.88E-06	2.91E-06	2.95E-06	2.98E-06	3.01E-06	3.04E-06	3.07E-06
3.00E-02	6.00E-04	2.33E-06	2.36E-06	2.39E-06	2.42E-06	2.45E-06	2.48E-06	2.51E-06	2.54E-06	2.57E-06	2.60E-06	2.64E-06	2.67E-06	2.70E-06	2.73E-06	2.76E-06	2.79E-06	2.82E-06	2.85E-06	2.88E-06	2.91E-06	2.95E-06	2.98E-06	3.01E-06	3.04E-06	3.07E-06
3.50E-02	7.00E-04	2.33E-06	2.36E-06	2.39E-06	2.42E-06	2.45E-06	2.48E-06	2.51E-06	2.54E-06	2.57E-06	2.60E-06	2.64E-06	2.67E-06	2.70E-06	2.73E-06	2.76E-06	2.79E-06	2.82E-06	2.85E-06	2.88E-06	2.91E-06	2.95E-06	2.98E-06	3.01E-06	3.04E-06	3.07E-06
4.00E-02	8.00E-04	2.33E-06	2.36E-06	2.39E-06	2.42E-06	2.45E-06	2.48E-06	2.51E-06	2.54E-06	2.57E-06	2.60E-06	2.64E-06	2.67E-06	2.70E-06	2.73E-06	2.76E-06	2.79E-06	2.82E-06	2.85E-06	2.88E-06	2.91E-06	2.95E-06	2.98E-06	3.01E-06	3.04E-06	3.07E-06
4.50E-02	9.00E-04	2.33E-06	2.36E-06	2.39E-06	2.42E-06	2.45E-06	2.48E-06	2.51E-06	2.54E-06	2.57E-06	2.60E-06	2.64E-06	2.67E-06	2.70E-06	2.73E-06	2.76E-06	2.79E-06	2.82E-06	2.85E-06	2.88E-06	2.91E-06	2.95E-06	2.98E-06	3.01E-06	3.04E-06	3.07E-06
5.00E-02	1.00E-03	2.33E-06	2.36E-06	2.39E-06	2.42E-06	2.45E-06	2.48E-06	2.51E-06	2.54E-06	2.57E-06	2.60E-06	2.64E-06	2.67E-06	2.70E-06	2.73E-06	2.76E-06	2.79E-06	2.82E-06	2.85E-06	2.88E-06	2.91E-06	2.95E-06	2.98E-06	3.01E-06	3.04E-06	3.07E-06

Extender Calculator – Selection

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

PZT-5H

SIDE LENGTH [sqrt(A)] TABLE (m):

t (m):	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	2.68E-03	2.66E-03	2.65E-03	2.63E-03	2.61E-03	2.60E-03	2.58E-03	2.56E-03	2.55E-03	2.53E-03	2.52E-03	2.50E-03	2.49E-03	2.48E-03	2.46E-03	2.45E-03	2.43E-03	2.42E-03	2.41E-03	2.40E-03	2.38E-03	2.37E-03	**2.36E-03**	2.35E-03	2.33E-03
1.10E-04	2.81E-03	2.79E-03	2.78E-03	2.76E-03	2.74E-03	2.72E-03	2.71E-03	2.69E-03	2.67E-03	2.66E-03	2.64E-03	2.63E-03	2.61E-03	2.60E-03	2.58E-03	2.57E-03	2.55E-03	2.54E-03	2.53E-03	2.51E-03	2.50E-03	2.49E-03	2.47E-03	2.46E-03	2.45E-03
1.20E-04	2.94E-03	2.92E-03	2.90E-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	2.74E-03	2.73E-03	2.71E-03	2.70E-03	2.68E-03	2.67E-03	2.65E-03	2.64E-03	2.62E-03	2.61E-03	2.60E-03	2.58E-03	2.57E-03	2.56E-03
1.30E-04	3.06E-03	3.04E-03	3.02E-03	3.00E-03	2.98E-03	2.96E-03	2.94E-03	2.92E-03	2.91E-03	2.89E-03	2.87E-03	2.86E-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	2.70E-03	2.69E-03	2.67E-03	2.66E-03
1.40E-04	3.17E-03	3.15E-03	3.13E-03	3.11E-03	3.09E-03	3.07E-03	3.05E-03	3.03E-03	3.02E-03	3.00E-03	2.98E-03	2.96E-03	2.95E-03	2.93E-03	2.91E-03	2.90E-03	2.88E-03	2.86E-03	2.85E-03	2.83E-03	2.82E-03	2.80E-03	2.79E-03	2.78E-03	2.76E-03
1.50E-04	3.28E-03	3.26E-03	3.24E-03	3.22E-03	3.20E-03	3.18E-03	3.16E-03	3.14E-03	3.12E-03	3.10E-03	3.09E-03	3.07E-03	3.05E-03	3.03E-03	3.01E-03	3.00E-03	2.98E-03	2.97E-03	2.95E-03	2.93E-03	2.92E-03	2.90E-03	2.89E-03	2.87E-03	2.86E-03
1.60E-04	3.39E-03	3.37E-03	3.35E-03	3.33E-03	3.31E-03	3.28E-03	3.26E-03	3.24E-03	3.22E-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	3.05E-03	3.03E-03	3.01E-03	3.00E-03	2.98E-03	2.97E-03	2.95E-03
1.70E-04	3.50E-03	3.47E-03	3.45E-03	3.43E-03	3.41E-03	3.39E-03	3.36E-03	3.34E-03	3.32E-03	3.30E-03	3.28E-03	3.27E-03	3.25E-03	3.23E-03	3.21E-03	3.19E-03	3.17E-03	3.16E-03	3.14E-03	3.12E-03	3.11E-03	3.09E-03	3.07E-03	3.06E-03	3.04E-03
1.80E-04	3.60E-03	3.57E-03	3.55E-03	3.53E-03	3.51E-03	3.48E-03	3.46E-03	3.44E-03	3.42E-03	3.40E-03	3.38E-03	3.36E-03	3.34E-03	3.32E-03	3.30E-03	3.28E-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
1.90E-04	3.70E-03	3.67E-03	3.65E-03	3.62E-03	3.60E-03	3.58E-03	3.56E-03	3.54E-03	3.51E-03	3.49E-03	3.47E-03	3.45E-03	3.43E-03	3.41E-03	3.39E-03	3.37E-03	3.36E-03	3.34E-03	3.32E-03	3.30E-03	3.28E-03	3.27E-03	3.25E-03	3.23E-03	3.22E-03
2.00E-04	3.79E-03	3.77E-03	3.74E-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	3.41E-03	3.39E-03	3.37E-03	3.35E-03	3.33E-03	3.32E-03	3.30E-03
2.10E-04	3.89E-03	3.86E-03	3.84E-03	3.81E-03	3.79E-03	3.76E-03	3.74E-03	3.72E-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	3.38E-03
2.20E-04	3.98E-03	3.95E-03	3.93E-03	3.90E-03	3.88E-03	3.85E-03	3.83E-03	3.80E-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	3.52E-03	3.50E-03	3.48E-03	3.46E-03
2.30E-04	4.07E-03	4.04E-03	4.01E-03	3.99E-03	3.96E-03	3.94E-03	3.91E-03	3.89E-03	3.87E-03	3.84E-03	3.82E-03	3.80E-03	3.78E-03	3.75E-03	3.73E-03	3.71E-03	3.69E-03	3.67E-03	3.65E-03	3.63E-03	3.61E-03	3.59E-03	3.58E-03	3.56E-03	3.54E-03
2.40E-04	4.15E-03	4.13E-03	4.10E-03	4.07E-03	4.05E-03	4.02E-03	4.00E-03	3.97E-03	3.95E-03	3.93E-03	3.90E-03	3.88E-03	3.86E-03	3.84E-03	3.81E-03	3.79E-03	3.77E-03	3.75E-03	3.73E-03	3.71E-03	3.69E-03	3.67E-03	3.65E-03	3.63E-03	3.62E-03
2.50E-04	4.24E-03	4.21E-03	4.18E-03	4.16E-03	4.13E-03	4.11E-03	4.08E-03	4.06E-03	4.03E-03	4.01E-03	3.98E-03	3.96E-03	3.94E-03	3.91E-03	3.89E-03	3.87E-03	3.85E-03	3.83E-03	3.81E-03	3.79E-03	3.77E-03	3.75E-03	3.73E-03	3.71E-03	3.69E-03

can be changed -> For n (L_s/t): 231

[d_0/2] (step distance) TABLE (m):

L_s (m):	t (m):	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
2.31E-02	1.00E-04	1.13E-05	1.14E-05	1.16E-05	1.17E-05	1.19E-05	1.20E-05	1.22E-05	1.23E-05	1.25E-05	1.26E-05	1.28E-05	1.29E-05	1.31E-05	1.32E-05	1.34E-05	1.35E-05	1.37E-05	1.38E-05	1.40E-05	1.41E-05	1.43E-05	1.44E-05	**1.46E-05**	1.47E-05	1.49E-05
2.54E-02	1.10E-04	1.13E-05	1.14E-05	1.16E-05	1.17E-05	1.19E-05	1.20E-05	1.22E-05	1.23E-05	1.25E-05	1.26E-05	1.28E-05	1.29E-05	1.31E-05	1.32E-05	1.34E-05	1.35E-05	1.37E-05	1.38E-05	1.40E-05	1.41E-05	1.43E-05	1.44E-05	1.46E-05	1.47E-05	1.49E-05
2.77E-02	1.20E-04	1.13E-05	1.14E-05	1.16E-05	1.17E-05	1.19E-05	1.20E-05	1.22E-05	1.23E-05	1.25E-05	1.26E-05	1.28E-05	1.29E-05	1.31E-05	1.32E-05	1.34E-05	1.35E-05	1.37E-05	1.38E-05	1.40E-05	1.41E-05	1.43E-05	1.44E-05	1.46E-05	1.47E-05	1.49E-05
3.00E-02	1.30E-04	1.13E-05	1.14E-05	1.16E-05	1.17E-05	1.19E-05	1.20E-05	1.22E-05	1.23E-05	1.25E-05	1.26E-05	1.28E-05	1.29E-05	1.31E-05	1.32E-05	1.34E-05	1.35E-05	1.37E-05	1.38E-05	1.40E-05	1.41E-05	1.43E-05	1.44E-05	1.46E-05	1.47E-05	1.49E-05
3.23E-02	1.40E-04	1.13E-05	1.14E-05	1.16E-05	1.17E-05	1.19E-05	1.20E-05	1.22E-05	1.23E-05	1.25E-05	1.26E-05	1.28E-05	1.29E-05	1.31E-05	1.32E-05	1.34E-05	1.35E-05	1.37E-05	1.38E-05	1.40E-05	1.41E-05	1.43E-05	1.44E-05	1.46E-05	1.47E-05	1.49E-05
3.47E-02	1.50E-04	1.13E-05	1.14E-05	1.16E-05	1.17E-05	1.19E-05	1.20E-05	1.22E-05	1.23E-05	1.25E-05	1.26E-05	1.28E-05	1.29E-05	1.31E-05	1.32E-05	1.34E-05	1.35E-05	1.37E-05	1.38E-05	1.40E-05	1.41E-05	1.43E-05	1.44E-05	1.46E-05	1.47E-05	1.49E-05
3.70E-02	1.60E-04	1.13E-05	1.14E-05	1.16E-05	1.17E-05	1.19E-05	1.20E-05	1.22E-05	1.23E-05	1.25E-05	1.26E-05	1.28E-05	1.29E-05	1.31E-05	1.32E-05	1.34E-05	1.35E-05	1.37E-05	1.38E-05	1.40E-05	1.41E-05	1.43E-05	1.44E-05	1.46E-05	1.47E-05	1.49E-05
3.93E-02	1.70E-04	1.13E-05	1.14E-05	1.16E-05	1.17E-05	1.19E-05	1.20E-05	1.22E-05	1.23E-05	1.25E-05	1.26E-05	1.28E-05	1.29E-05	1.31E-05	1.32E-05	1.34E-05	1.35E-05	1.37E-05	1.38E-05	1.40E-05	1.41E-05	1.43E-05	1.44E-05	1.46E-05	1.47E-05	1.49E-05
4.16E-02	1.80E-04	1.13E-05	1.14E-05	1.16E-05	1.17E-05	1.19E-05	1.20E-05	1.22E-05	1.23E-05	1.25E-05	1.26E-05	1.28E-05	1.29E-05	1.31E-05	1.32E-05	1.34E-05	1.35E-05	1.37E-05	1.38E-05	1.40E-05	1.41E-05	1.43E-05	1.44E-05	1.46E-05	1.47E-05	1.49E-05
4.39E-02	1.90E-04	1.13E-05	1.14E-05	1.16E-05	1.17E-05	1.19E-05	1.20E-05	1.22E-05	1.23E-05	1.25E-05	1.26E-05	1.28E-05	1.29E-05	1.31E-05	1.32E-05	1.34E-05	1.35E-05	1.37E-05	1.38E-05	1.40E-05	1.41E-05	1.43E-05	1.44E-05	1.46E-05	1.47E-05	1.49E-05
4.62E-02	2.00E-04	1.13E-05	1.14E-05	1.16E-05	1.17E-05	1.19E-05	1.20E-05	1.22E-05	1.23E-05	1.25E-05	1.26E-05	1.28E-05	1.29E-05	1.31E-05	1.32E-05	1.34E-05	1.35E-05	1.37E-05	1.38E-05	1.40E-05	1.41E-05	1.43E-05	1.44E-05	1.46E-05	1.47E-05	1.49E-05
4.85E-02	2.10E-04	1.13E-05	1.14E-05	1.16E-05	1.17E-05	1.19E-05	1.20E-05	1.22E-05	1.23E-05	1.25E-05	1.26E-05	1.28E-05	1.29E-05	1.31E-05	1.32E-05	1.34E-05	1.35E-05	1.37E-05	1.38E-05	1.40E-05	1.41E-05	1.43E-05	1.44E-05	1.46E-05	1.47E-05	1.49E-05
5.08E-02	2.20E-04	1.13E-05	1.14E-05	1.16E-05	1.17E-05	1.19E-05	1.20E-05	1.22E-05	1.23E-05	1.25E-05	1.26E-05	1.28E-05	1.29E-05	1.31E-05	1.32E-05	1.34E-05	1.35E-05	1.37E-05	1.38E-05	1.40E-05	1.41E-05	1.43E-05	1.44E-05	1.46E-05	1.47E-05	1.49E-05
5.31E-02	2.30E-04	1.13E-05	1.14E-05	1.16E-05	1.17E-05	1.19E-05	1.20E-05	1.22E-05	1.23E-05	1.25E-05	1.26E-05	1.28E-05	1.29E-05	1.31E-05	1.32E-05	1.34E-05	1.35E-05	1.37E-05	1.38E-05	1.40E-05	1.41E-05	1.43E-05	1.44E-05	1.46E-05	1.47E-05	1.49E-05
5.54E-02	2.40E-04	1.13E-05	1.14E-05	1.16E-05	1.17E-05	1.19E-05	1.20E-05	1.22E-05	1.23E-05	1.25E-05	1.26E-05	1.28E-05	1.29E-05	1.31E-05	1.32E-05	1.34E-05	1.35E-05	1.37E-05	1.38E-05	1.40E-05	1.41E-05	1.43E-05	1.44E-05	1.46E-05	1.47E-05	1.49E-05
5.78E-02	2.50E-04	1.13E-05	1.14E-05	1.16E-05	1.17E-05	1.19E-05	1.20E-05	1.22E-05	1.23E-05	1.25E-05	1.26E-05	1.28E-05	1.29E-05	1.31E-05	1.32E-05	1.34E-05	1.35E-05	1.37E-05	1.38E-05	1.40E-05	1.41E-05	1.43E-05	1.44E-05	1.46E-05	1.47E-05	1.49E-05

Brake and Extender Characteristics

Brake Selection:

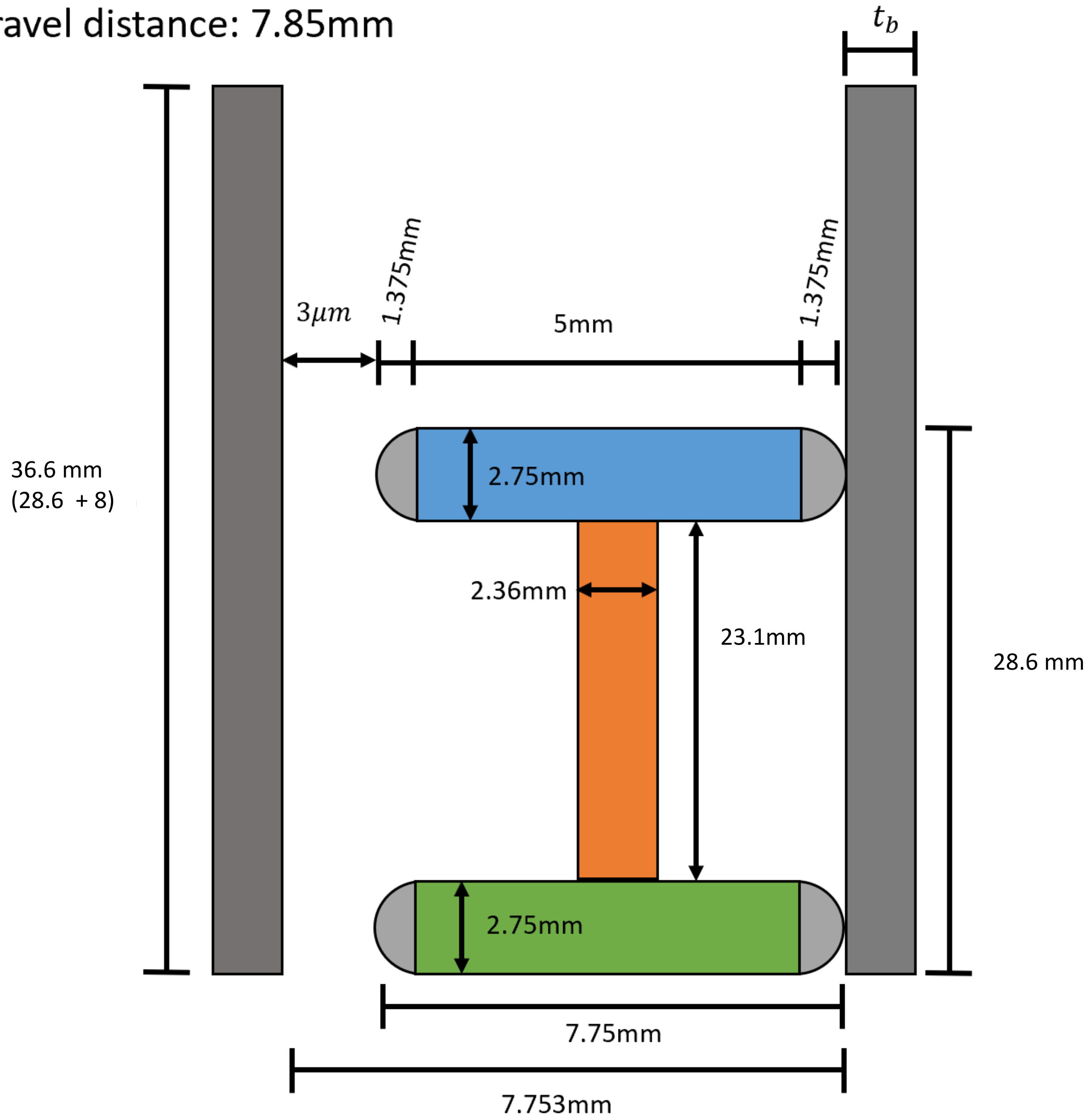
- APC 856 (material selected)
- $\mathrm{V} = 194\ V$ (operating voltage)
- $side\ length\ (\sqrt{A}) = 2.75\ mm$
- $t = 0.1\ mm$
- $n = 50$
- $L_s = 5\ mm$
- $F_3 = \frac{f_{bl}}{2} = 266\ N$
- $\frac{\delta_0}{2} = 3.01\ \mu m$
  - Therefore we can use a bore with 3 μm clearance

Extender Selection:

- PZT-5H (material selected)
- $\mathrm{V} = 194\ V$ (operating voltage)
- $side\ length\ (\sqrt{A}) = 2.36\ mm$
- $t = 0.1\ mm$
- $n = 231$
- $L_s = 23.1\ mm$
- $step\ size\ [at\ max.load] = \frac{\delta_0}{2} = 14.56\ \mu m$

Section 3:
Packaging of Actuator

Travel distance: 7.85mm



Actuator Size

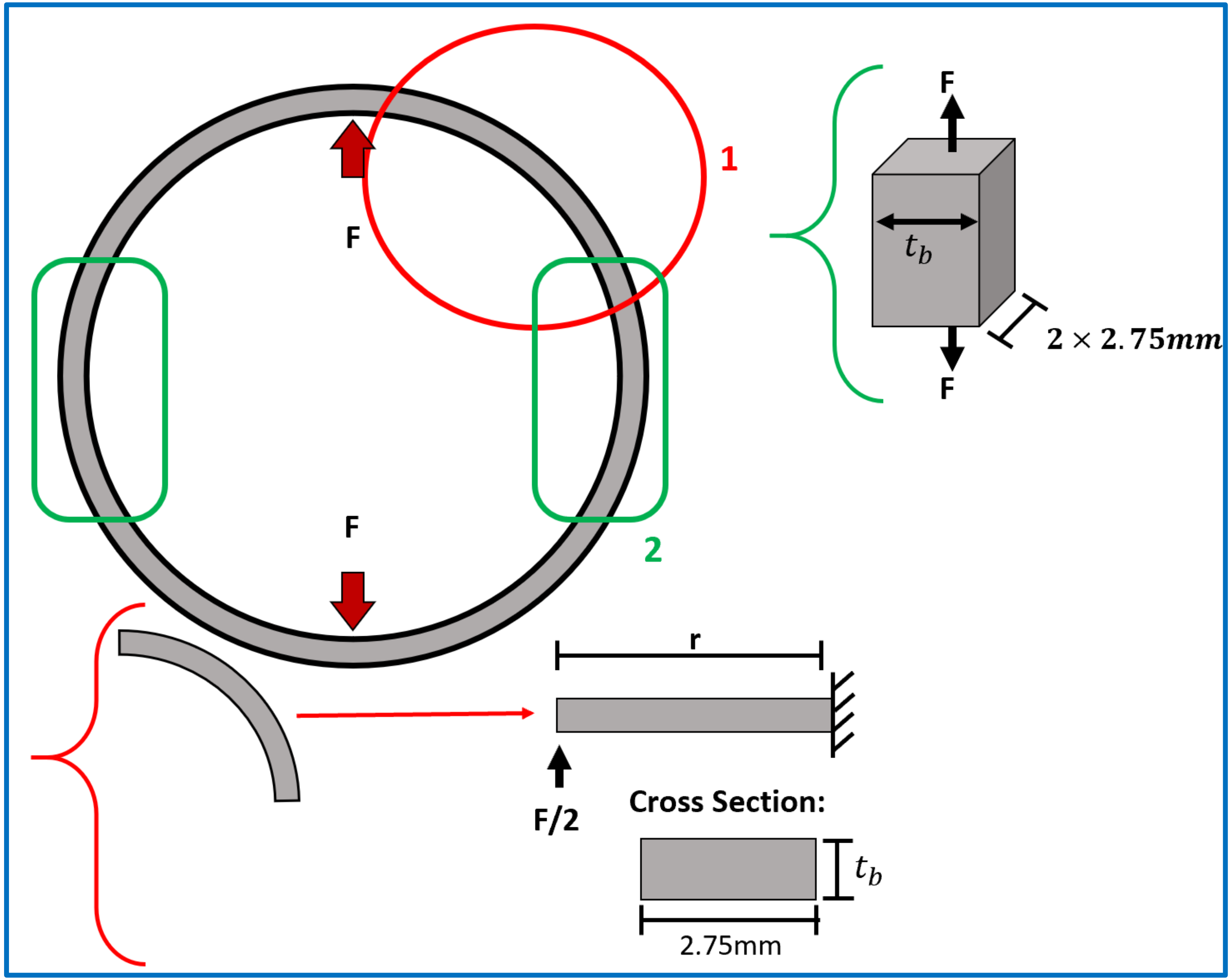
NEXT STEP:

determine wall thickness

266 N load from brake

Tube Thickness Approximation

- $F = 266\ N$
- $r = 2.75mm = 0.00275m$
- SAE 980X steel
  - $\sigma_y = 552\ MPa = 552 \times 10^6\ Pa$
- Case 1:
  - $\sigma_{max} = \dfrac{\frac{F}{2} \times r \times \left(\frac{t_b}{2}\right)}{\left(\frac{0.00275 \times t_b^3}{12}\right)}$
  - $t_b \geq \sqrt{\dfrac{3 \times F \times r}{0.00275 \times \sigma_y}} = 1.4275mm$
- Case 2:
  - $\sigma_{max} = \dfrac{F}{t_b(2 \times 0.00275)}$
  - $t_b \geq \dfrac{F}{\sigma_y(2 \times 0.00275)} = 0.0876mm$
- So, $t_b \geq 1.4275mm$ Therefore…
  - Let, $\boldsymbol{t_b = 3mm}$



Actuator and Component Mass

- Brake (M_{brake}):
  - $\rho_{APC\ 856} \times A_{brake} \times L_{s(brake)}$
  - $7.5 \frac{g}{cm^3} \times (2.75mm)^2 \times 5mm = \mathbf{0.2836g}$
- Extender ($M_{extender}$):
  - $\rho_{PZT-5H} \times A_{extender} \times L_{s(extender)}$
  - $7.87 \frac{g}{cm^3} \times (2.36mm)^2 \times 23.1mm = \mathbf{1.0125g}$
- Contact Pads ($M_{contacts}$):
  - $\rho_{steel} \times \frac{\frac{4}{3}\pi r^3}{2}$
  - $8.05 \frac{g}{cm^3} \times \frac{4}{3}\pi(1.375mm)^3/2 = \mathbf{0.0438g}$
- Tube (M_{tube}):
  - $\rho_{steel}\left(H_{tube}\left[\pi\left(\frac{D}{2}\right)^2 - \pi\left(\frac{d}{2}\right)^2\right]\right)$
  - $8.05 \frac{g}{cm^3}\left(36.6mm\left[\pi\left(\frac{7.753+(2*3mm)}{2}\right)^2 - \pi\left(\frac{7.753}{2}\right)^2\right]\right) = \mathbf{29.8592g}$
- Actuator ($M_{actuator}$):
  - $M_{actuator} = 2M_{brake} + M_{extender} + 4M_{contacts} + M_{tube} = \mathbf{31.6141\ g}$

Section 4:
Actuation Speed Modeling

Transducer Equations for Stack Actuator

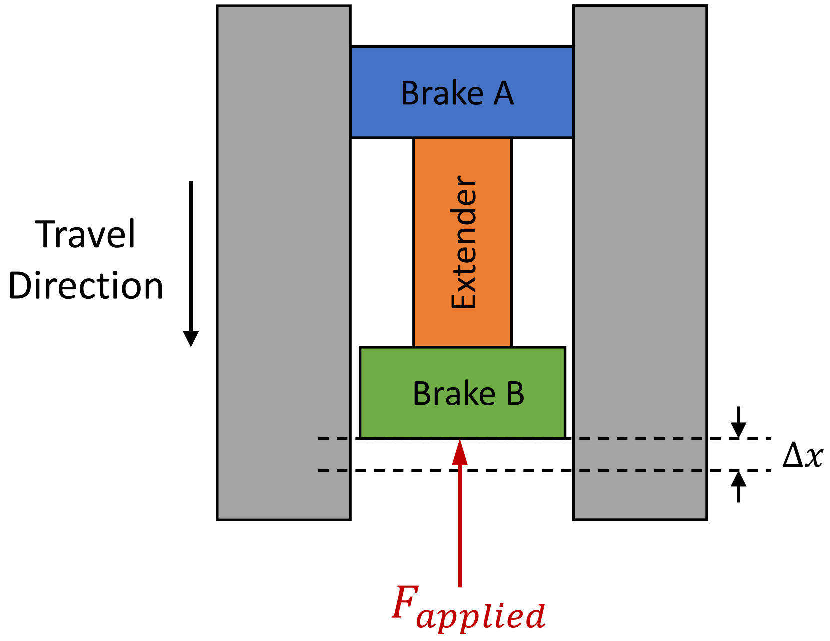
- First step in modeling the extension speed of the piezo stack is to look at extension versus applied force.

$$S = s^E T + d_{33} E = s^E \frac{-F}{A} + d_{33} \frac{V_{in}}{t_p}$$

$$\frac{\Delta x}{n t_p} = s^E \frac{-F}{A} + d_{33} \frac{V_{in}}{t_p}$$

$$F = \frac{n d_{33} A}{n t_p s^E} V_{in} - \frac{\Delta x A}{n t_p s^E} = n d_{33} K_a V_{in} - \Delta x K_a$$

$$\boldsymbol{\Delta x = n d_{33} V_{in} - \frac{F}{K_a}}$$



(Edinger et al. 2000)
(Ling et al. 1998)

Transducer Equations for Stack Actuator

- First step in modeling the extension speed of the piezo stack is to look at extension versus applied force.

$$S = s^E T + d_{33} E = s^E \frac{-F}{A} + d_{33} \frac{V_{in}}{t_p}$$

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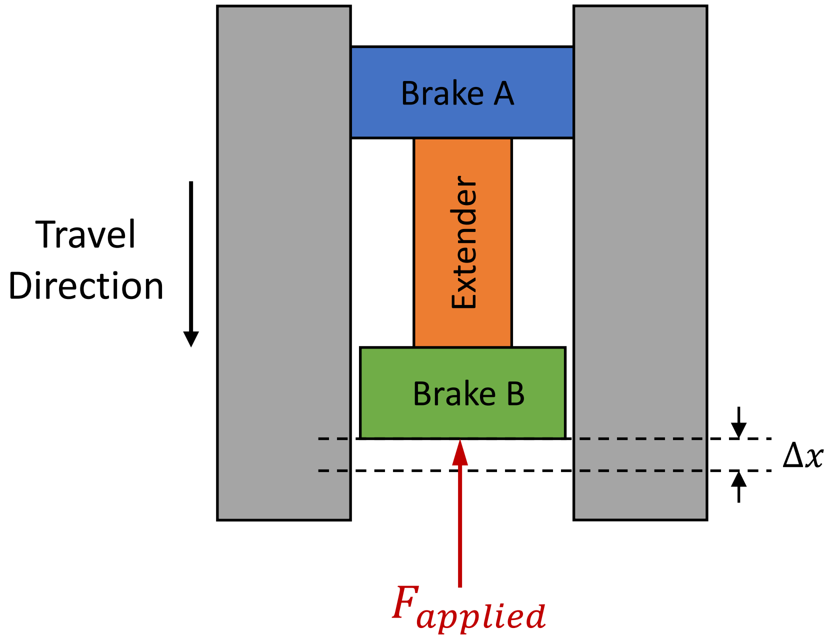
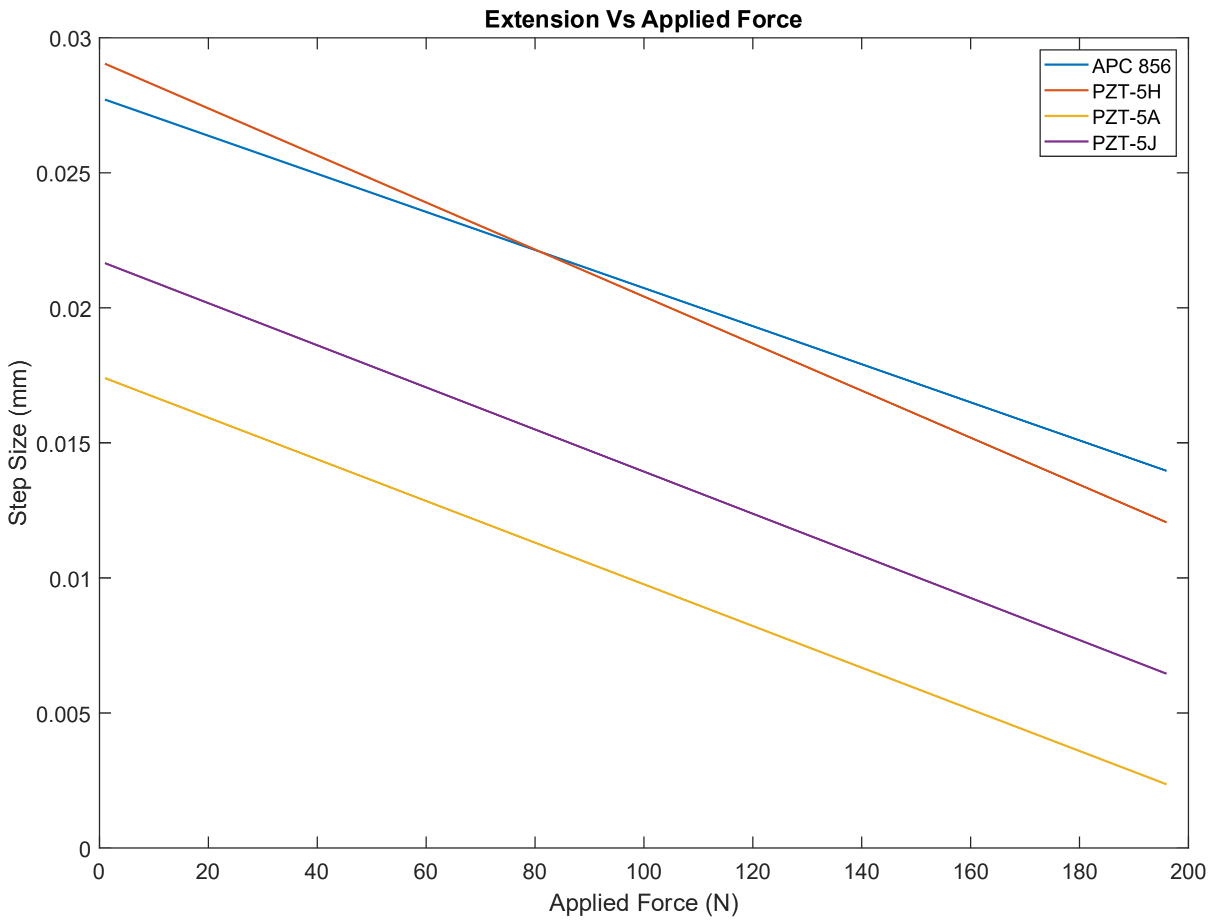
$$\boldsymbol{\Delta x = n d_{33} V_{in} - \frac{F}{K_a}}$$



Step size vs Applied Force

- Analyse the extending piezo actuator's performance at different finger loads.
- APC 856 has a higher step size at higher loads.
- PZT-5H has a higher step size at lower loads.
- $\mathrm{V} = 194\ V$ (operating voltage)
- $side\ length\ (\sqrt{A}) = 2.36\ mm$
- $t = 0.1\ mm$
- $n = 231$



Time Response

- We can determine how much the extender will change length as a function of applied force -> How long will it take?

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

Resonant Frequency (without load) [Hz]

$$f_0' = f_o \sqrt{\frac{\frac{m}{3}}{\frac{m}{3} + M}}$$

m = mass of actuator
M = mass of additional load

Worst Case Analysis: How will resonant frequency change with a 10 kg mass sitting on the stack? Actuator mass is roughly 20 grams.

$$f_o' = f_o \sqrt{\frac{\frac{20 \times 10^{-3}}{3}}{\frac{20 \times 10^{-3}}{3} + 10}} = 0.0258 f_o$$

(PI Ceramic, n.d.)

Time Response

$t_{e,unloaded} \approx 8.33\ \mu s$
$t_{b,unloaded} \approx 2.47\ \mu s$
$T_{unloaded} \approx 26.5\ \mu s$
$T_{unloaded}^{-1} \approx 37{,}700\ Hz$

$t_{e,loaded} \approx 323.00\ \mu s$
$t_{b,loaded} \approx 95.68\ \mu s$
$T_{loaded} \approx 1.03\ ms$
$T_{loaded}^{-1} \approx 972\ Hz$

Actuator	Dimensions [mm]	Nominal Displacement [um]	Blocked Force [N]	Resonant Frequency, f_0 [Hz]	Loaded Frequency $0.026 f_o$ [Hz]
Equivalent piezo for brakes: P-883.11	3 x 3 x 9	6.5	290	135,000	3,484
Equivalent piezo for extender: P-885.91	5 x 5 x 36	32	950	40,000	1,032

$$V_{avg} = \Delta l_{extender,\, per\ cycle} \times f_{actuator} = 29.1 \times 10^{-3}\ mm \times 300\ Hz = 8.73\ \text{mm/s}$$

Even in the worst-case example (10 kg mass on all actuators), we are operating the actuator far away from its loaded resonance frequency. It is safe to assume that the only limiting factor in the time response will be the driving frequency.

(PI Ceramic, n.d.)

Simulation Script

- As the inchworm moves along its track, the applied force increases due to the return spring in the joint.
- A script was created to iteratively solve for a new applied force and the corresponding step height.

Material properties and geometries defined →

```
%Config - 1
stack.config_1.Material = "APC 856";
stack.config_1.d33 = 6.20*10^-10;    %Strain coefficient
stack.config_1.s33 = 1.7*10^-11;     %Elastic compliance
stack.config_1.side = 2.36;          %Side length (square) in mm
stack.config_1.t = 0.1;              %Thickness of element in mm
stack.config_1.n = 100;              %Number of stacked elements
```

Simulation Parameters →

```
Hz.Extender = 300;      %Hz
Hz.Brake = 300;         %Hz
K_spring = 0.76;        %N/mm
F_Pre = 1;              %1N pretension
Force_applied = 167;    %Newtons
SimTime = 1;            %seconds
```

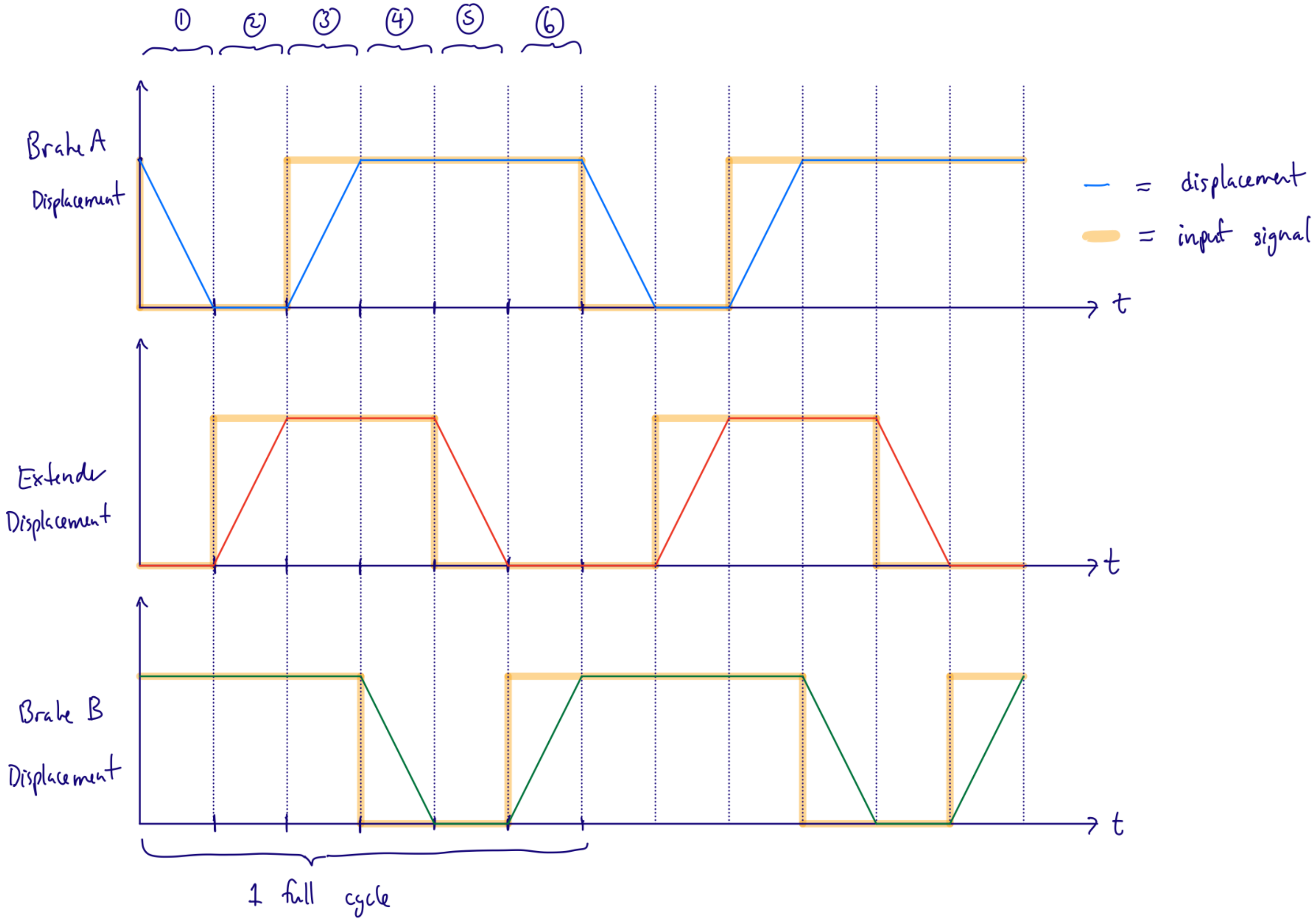
Piezo Response →

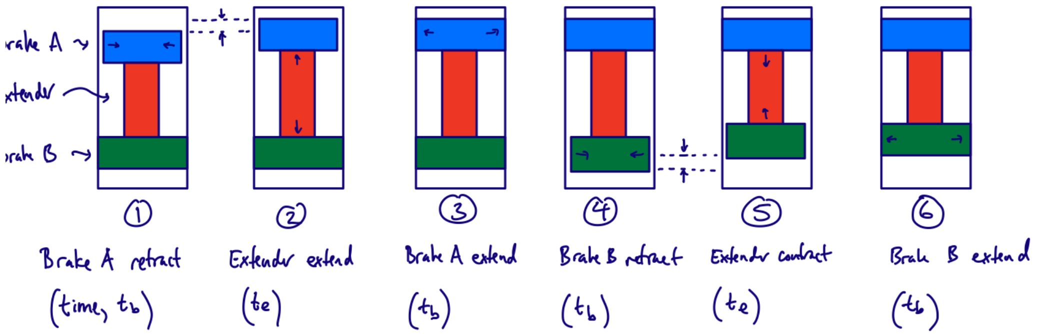
```
% Characteristics of Extender
T.Extender = 8.33e-6;                  %s
T.Brake = 2.47e-6;                     %s

T.Theo = 2*T.Extender + 4*T.Brake;     %s
T.Act = 1/Hz.Extender;                 %s
T.Idle = T.Act - T.Theo;               %s
```

Iterative Solver:

- Step 1: Top brakes disengage
- Step 2: Extender actuating
- Step 3: Front brakes engaging
- Step 4: Bottom brakes disengaging
- Step 5: Extender contracting
- Step 6: Bottom brakes engage

Inchworm Background Recap





Cycle period:

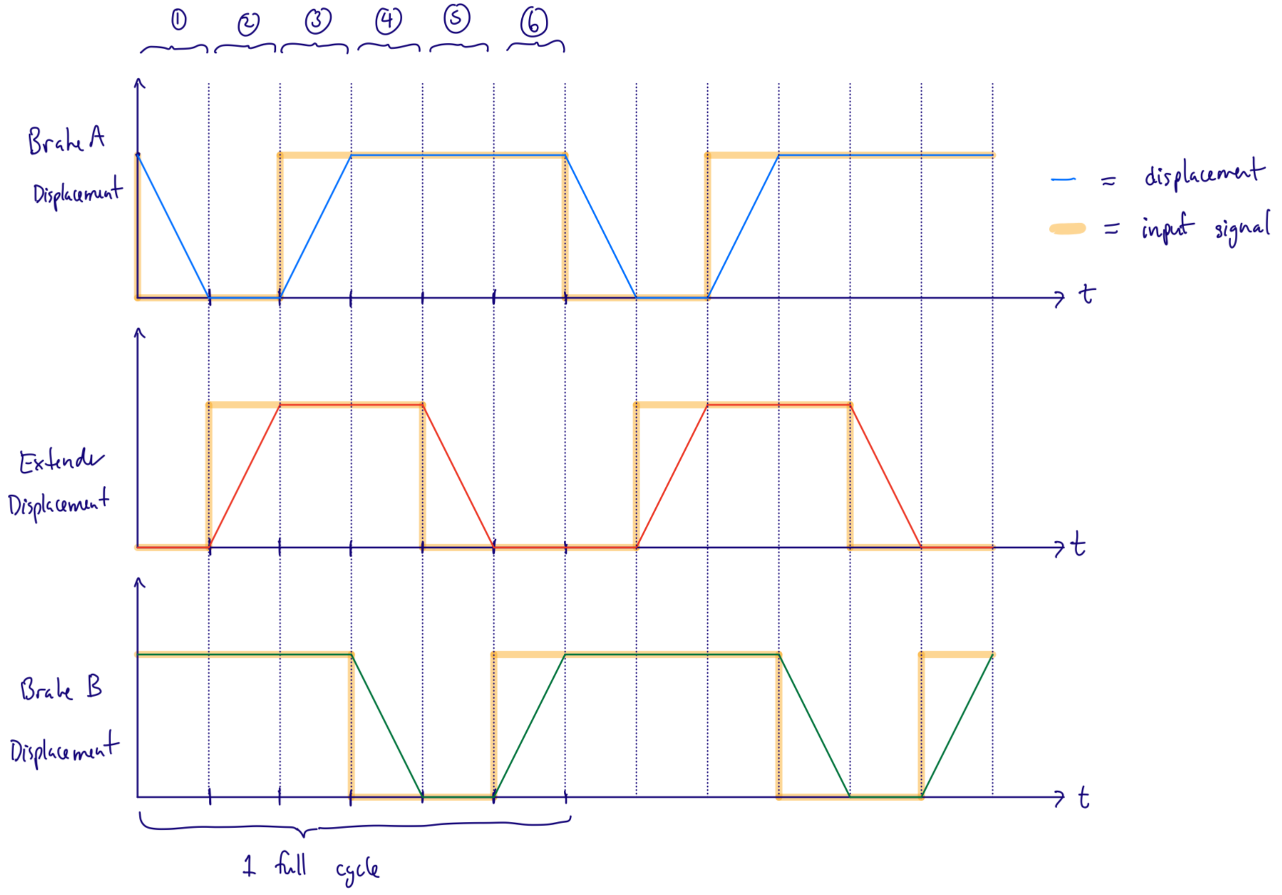
$$T = 2t_e + 4t_b$$

Average Actuation Speed:

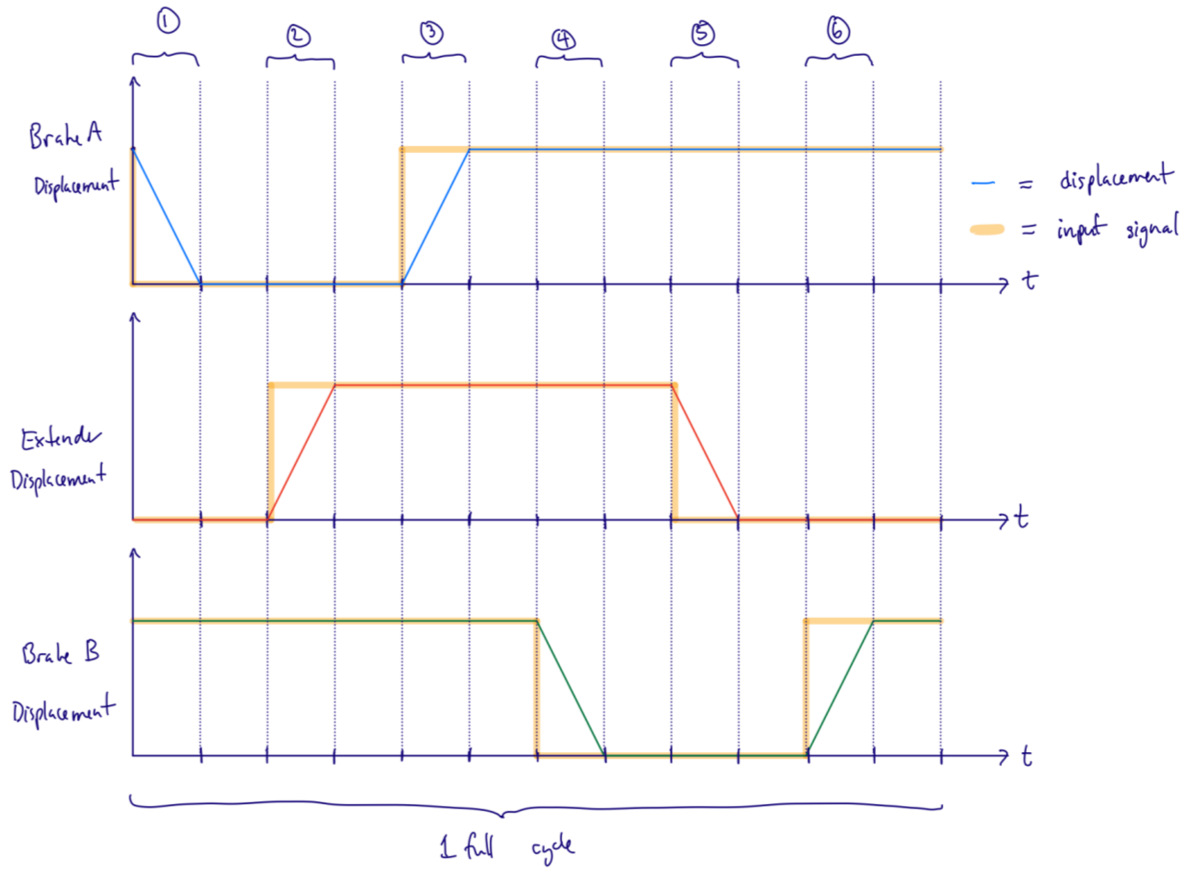
$$V_{avg} = \frac{\Delta l_{extender,\, per\ cycle}}{T}$$

Inchworm Background Recap (cont'd)

Maximum Theoretical Actuation Speed

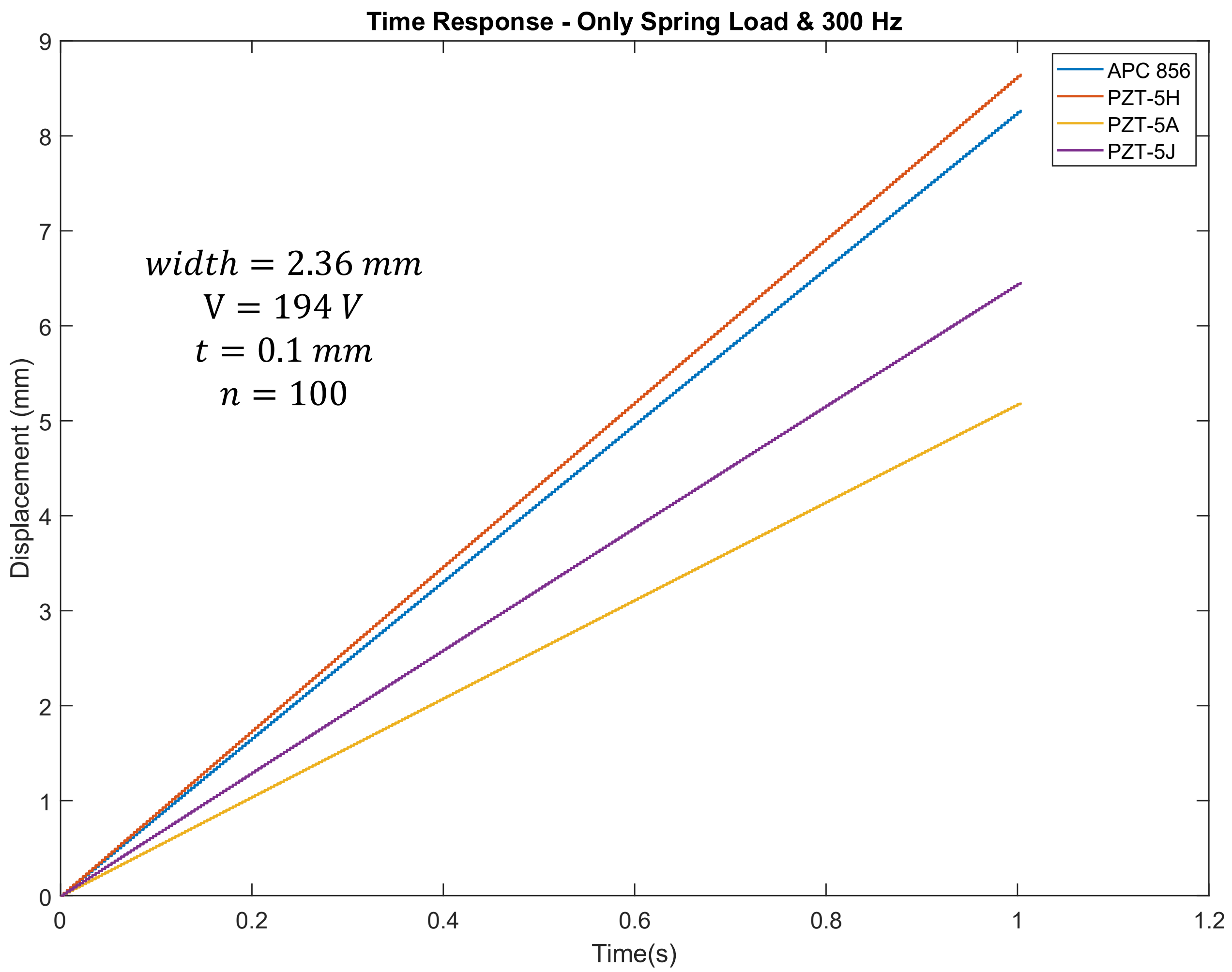


Reduced Actuation Speed



Results

- Results show the expected step response.
- Even though APC 856 has a larger step at higher applied force, it does not lead to a faster inchworm.
- Plot confirms that PZT-5H is the best option.
- Full load over the entire cycle is unrealistic.
- Driving frequency of 300 Hz



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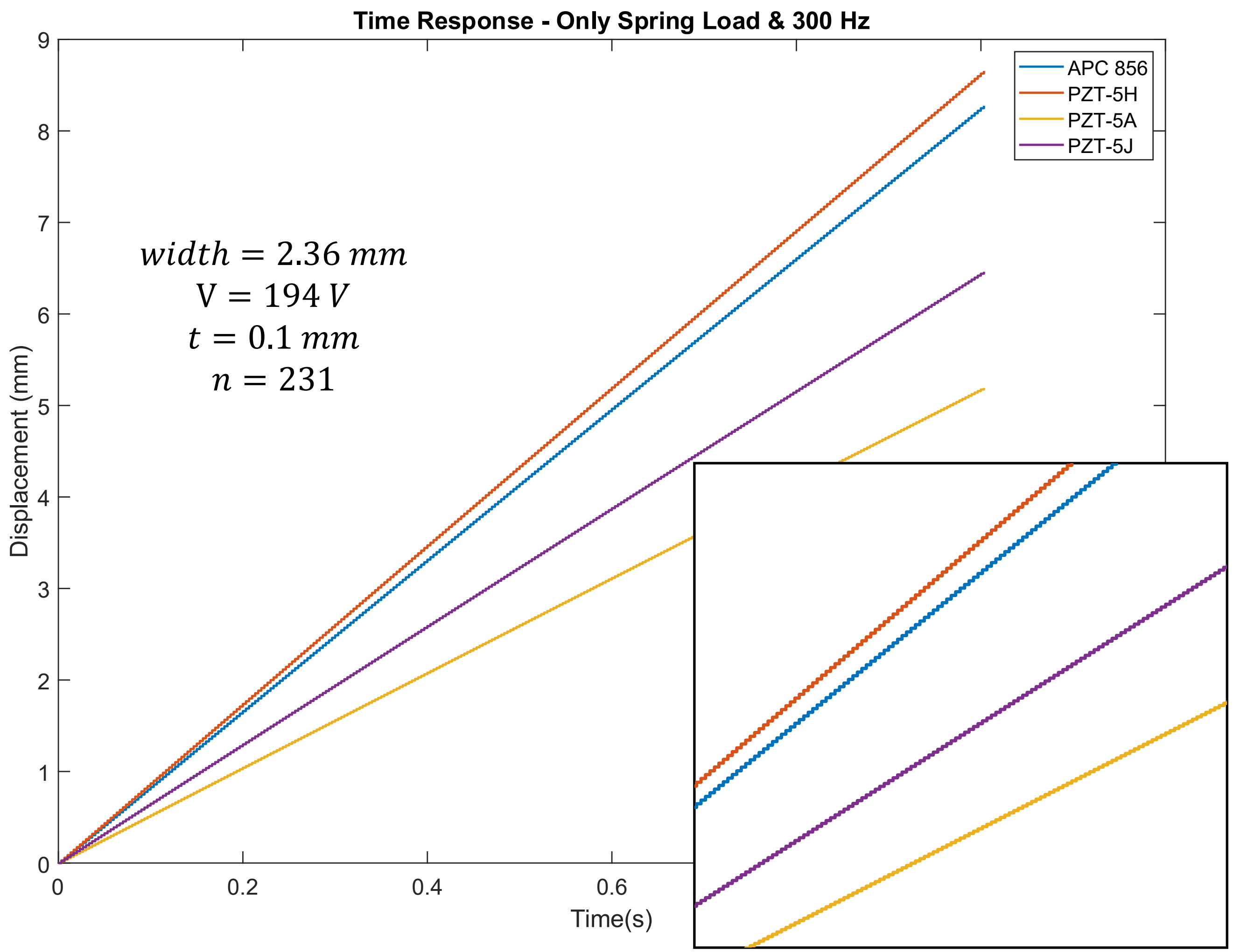
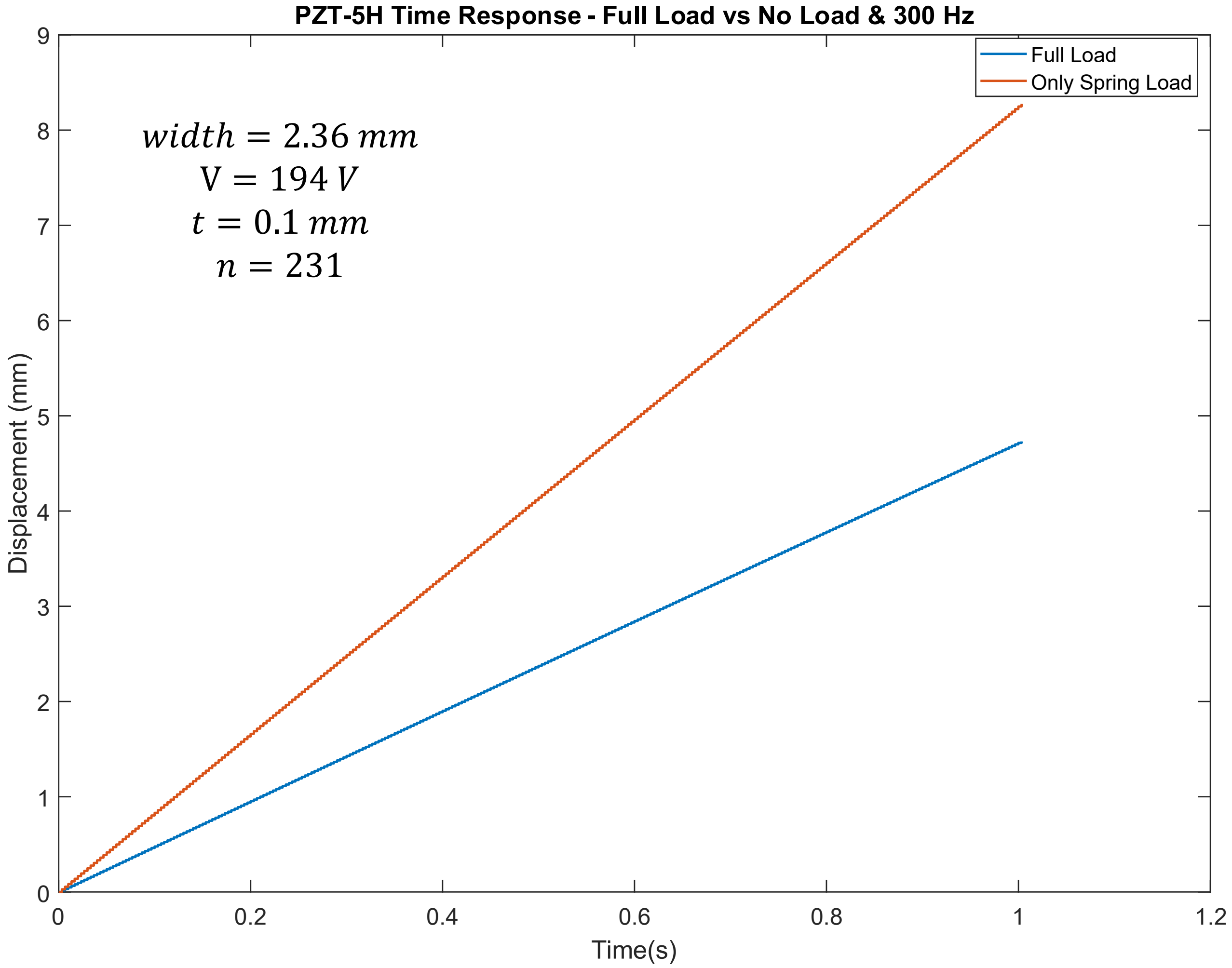


Results

- We would operate somewhere between the two curves depending on force applied at the fingertips
- i.e. closing quickly against no load followed by slow closing against applied load

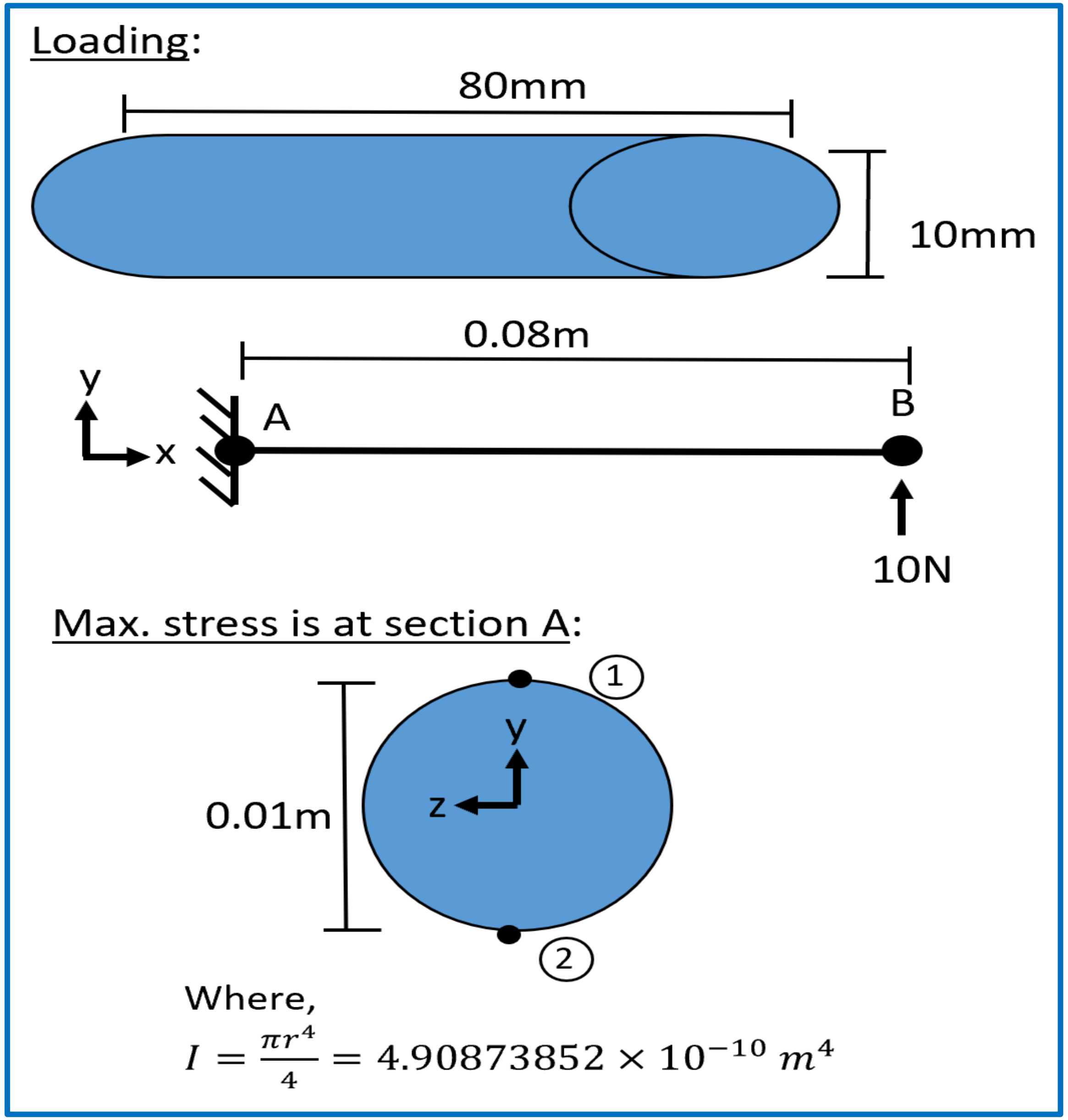


Section 5:
High Level Prosthetic Overview

Finger Stress Analysis

- Loading:
  - $+\uparrow \sum F_y = 0;\ 0 = F_{By} + F_{Ay} = 10N + F_{Ay} \rightarrow F_{Ay} = -10N$
  - $+_{ccw} \sum M_{@A} = 0; M_{@A} = 0 = 10N \times 0.08m = 0.8Nm$

- Stresses:
  - Worst case compression (point 1):
    - $\sigma_C = \frac{-M_A \times (0.005m)}{I} = -8.1487\ MPa$
  - Worst case tension (point 2):
    - $\sigma_T = \frac{-M_A \times (-0.005m)}{I} = +8.1487\ MPa$



Acceptable Structural Materials

- We wanted to explore using polymers, as they are lightweight and inexpensive
- As we can see, every polymer is able to withstand the necessary finger loading

Polymer Type	Compressive Yield Strength (MPa)	Compressive Modulus (GPa)
ABS	65	2.5
ABS + 30% Glass Fiber	120	8
Acetal Copolymer	85	2.2
Acetal Copolymer + 30% Glass Fiber	100	7.5
Acrylic	95	3
Nylon 6	55	2.3
Polyamide-Imide	130	5
Polycarbonate	70	2.0
Polyethylene, HDPE	20	0.7
Polyethylene Terephthalate (PET)	80	1
Polyimide	150	2.5
Polyimide + Glass Fiber	220	12
Polypropylene	40	1.5
Polystyrene	70	2.5

http://www.matweb.com/reference/compressivestrength.aspx

Polymer Type	Ultimate Tensile Strength (MPa)	Elongation (%)	Tensile Modulus (GPa)
ABS	40	30	2.3
ABS + 30% Glass Fiber	60	2	9
Acetal Copolymer	60	45	2.7
Acetal Copolymer + 30% Glass Fiber	110	3	9.5
Acrylic	70	5	3.2
Nylon 6	70	90	1.8
Polyamide-Imide	110	6	4.5
Polycarbonate	70	100	2.6
Polyethylene, HDPE	15	500	0.8
Polyethylene Terephthalate (PET)	55	125	2.7
Polyimide	85	7	2.5
Polyimide + Glass Fiber	150	2	12
Polypropylene	40	100	1.9
Polystyrene	40	7	3

http://www.matweb.com/reference/tensilestrength.aspx

Section 6:
Comparison and Conclusion

Direct Comparison

Actual Hand

- Density of Human Hand:
  - Hands have little fat content, and are comprised of mostly muscle and bone tissue. So, we will need those densities to determine the density of a human hand
  - The density of bone is 1.9 g/cc, but this neglects its porosity, the practical density of bone is ~1.0 g/cc
  - The density of muscle is about 1.0597 g/cc
  - If we want to lightest possible case, to compare our prosthetic with
    - Lowest hand density ($\rho_{hand(low)}$) ≈**1.0 g/cc**

Prosthetic Hand

- Density of Polymers:

PP – 0.91 g/cc

ABS – 1.21 g/cc

PET – 1.40 g/cc

HDPE – 0.970 g/cc

PI(polyimide) – 1.431 g/cc

POM(Acetal) – 1.42 g/cc

- PP is the best choice, it is stronger, stiffer, and lighter than HDPE, it also has relatively good dimensional stability (low water absorption)

Comparison to Levinson, 2009

- 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)

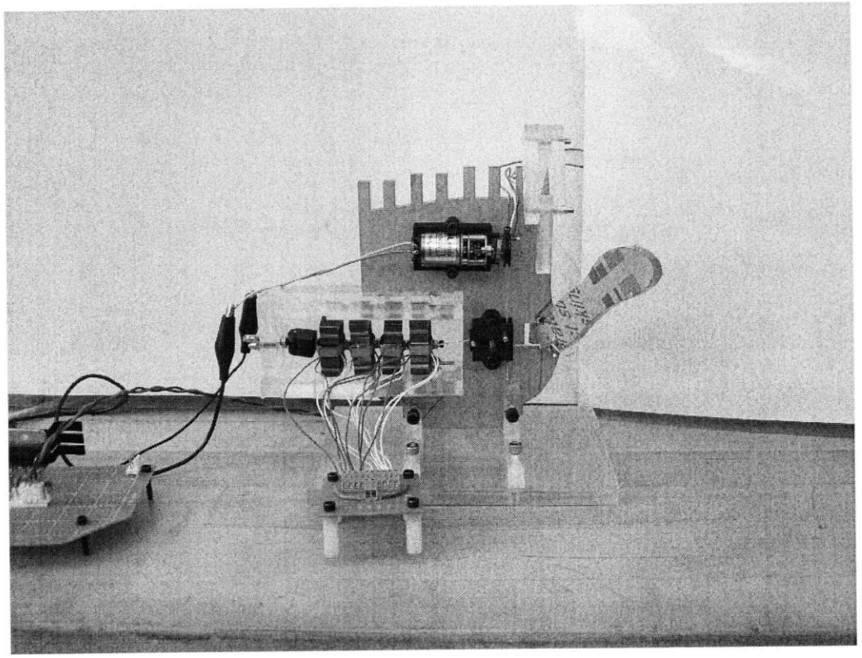


Figure 11. Front view of fully assembled hybrid DC motor/PZT actuator prototype.

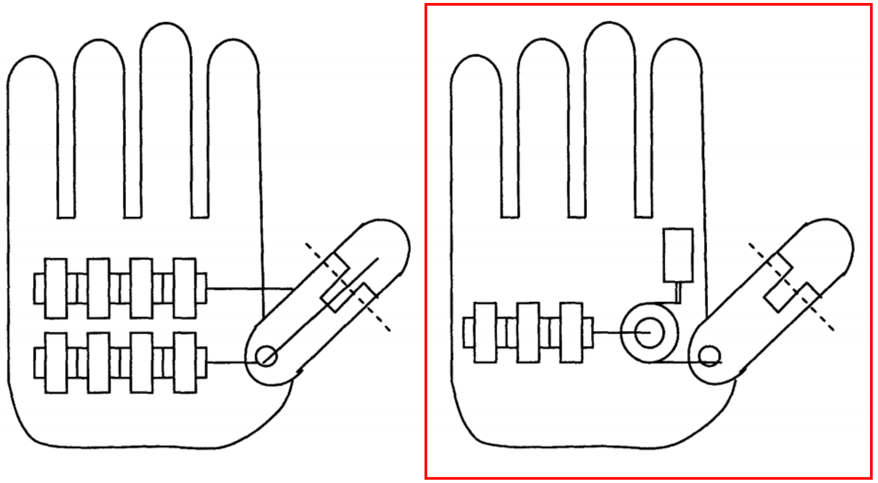


Figure 10. Potential design implementations: PZT actuator driven (left), hybrid DC motor/PZT actuator(right).

(Levinson, 2009)

Comparison to Levinson, 2009

- 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

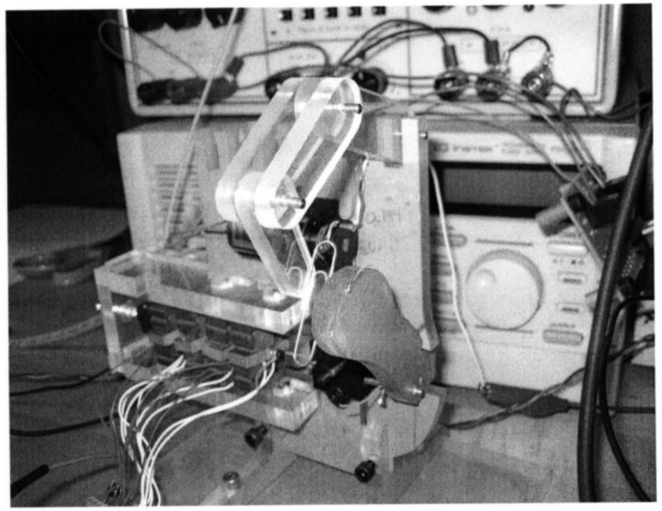
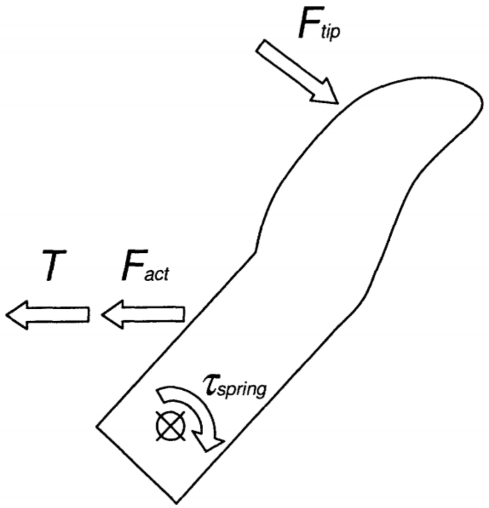


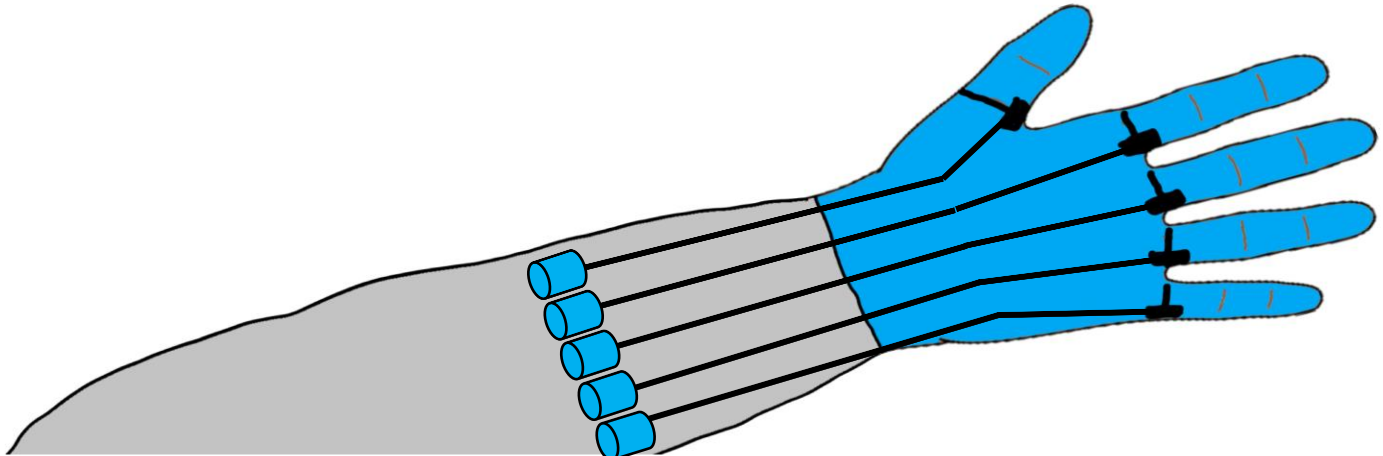
Figure 17. Thumb prototype pinching a paperclip.

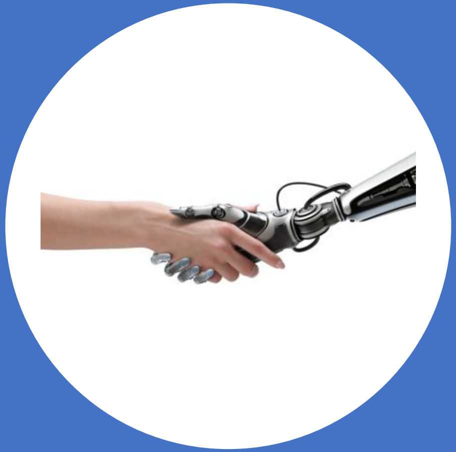


(Levinson, 2009)

Benefits of Inchworm and Practicality

- It is likely that our solution will have a lower rejection rate than existing prosthetic solutions, as it solves the following problems…
  - Light weight
  - Unobtrusive (not bulky)
  - Flexibility of design allows for actuators to be mounted away from prosthetic hand (e.g. on/around forearm) keeping the design light and simple





Thank You!

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