Design and Analysis of a Practical Large-Force Piezoelectric Inchworm Motor with a Novel Force Duplicator

M.Eng Dissertation – EF Williams
Submitted to University of Pretoria Department of Mechanical and Aeronautical Engineering

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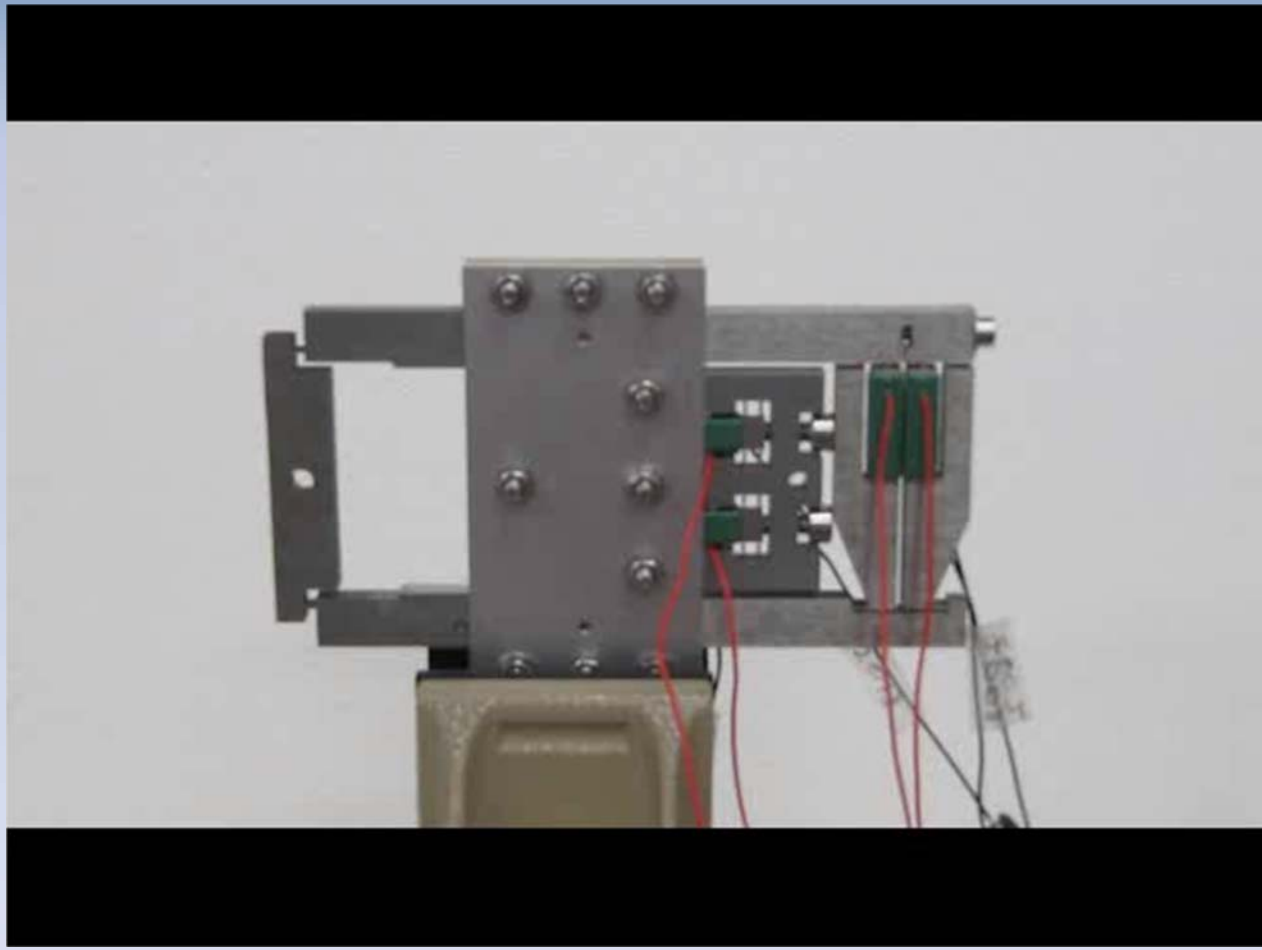
Presentation Outline

- About Piezoelectrical materials
- Piezoelectrical Behaviour
- Piezoelectrical Actuators
- Introduction to Inchworm motors
- Load limit of an Inchworm motor
- Testing of the Inchworm motor
- Conclusion

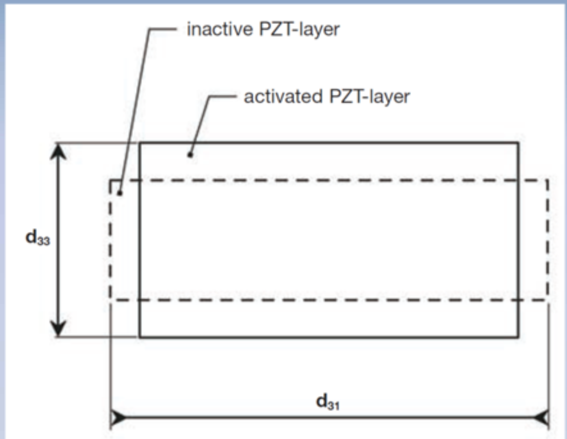
…… but first, what is an Piezoelectrical Inchworm motor?

An Inchworm motor



About Piezoelectrical Materials

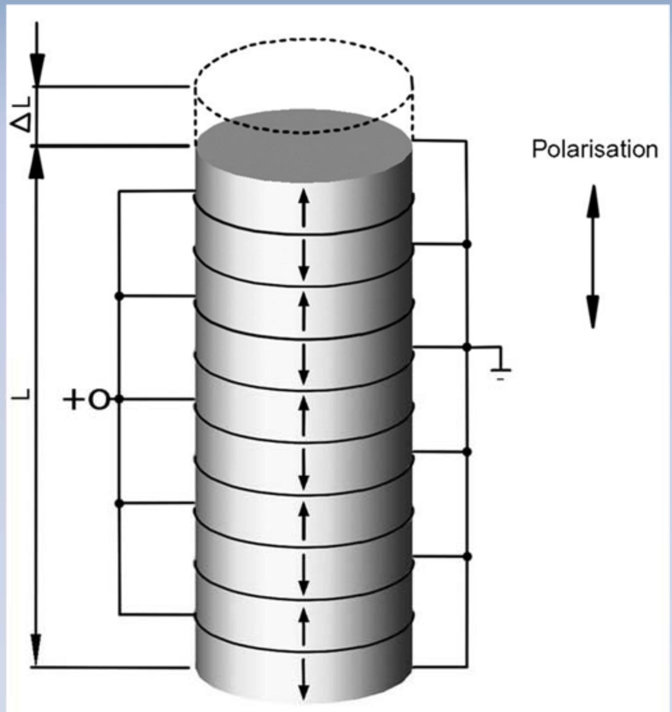
Typical deformation of a piezoelectric material



$$\Delta L = \pm E_3 \cdot d_{33} \cdot L_0 = \pm V \cdot d_{33}$$

(Piezomechanik, 2011)

Electrical design of a stack actuator



$$\Delta L = \pm E_3 \cdot d_{33} \cdot L_0 \cdot N$$

(Physikinstrumente," 2011)

Piezoelectrical Behaviour

$$S = s^E \cdot T + d^t \cdot E$$

$$D = d \cdot T + \varepsilon^T \cdot E$$

(Meeker, T. R. (1996).
IEEE Standard on Piezoelectricity)

$$S_3 = s_{33}^E \cdot T_3 + d_{33} \cdot E_3$$

$$S_3 = \frac{\delta}{L} \qquad E_3 = \frac{V_{out}}{L} \qquad T_3 = \frac{F}{area}$$

$$\delta = \frac{s_{33}^E \cdot L}{area} \cdot F + d_{33} \cdot V$$

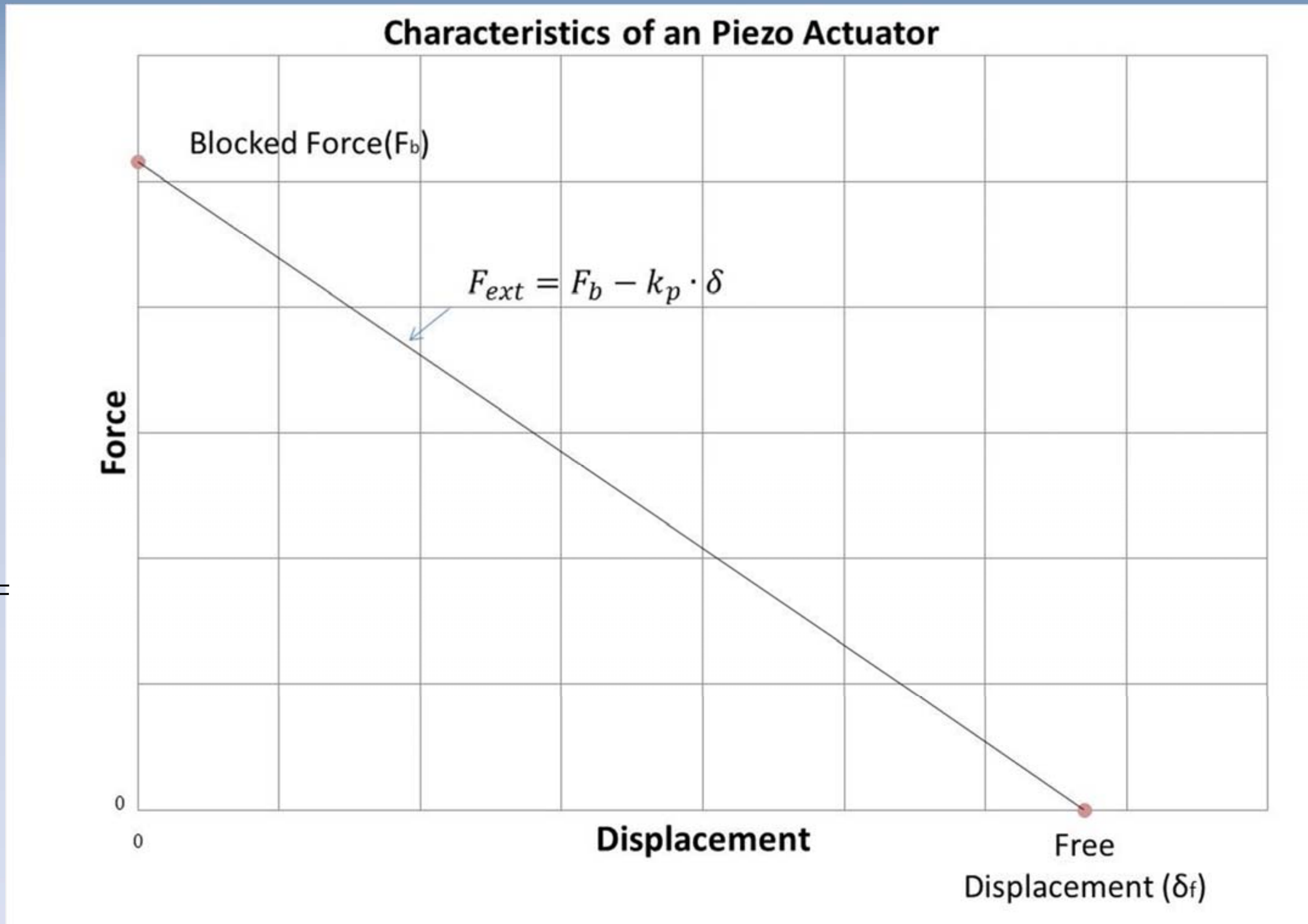
$$\delta = a \cdot F + b \cdot V$$

a is the compliance
b is the ration between δ and V when F is constant

$$F = k_p \cdot \delta - k_p \cdot b \cdot V$$

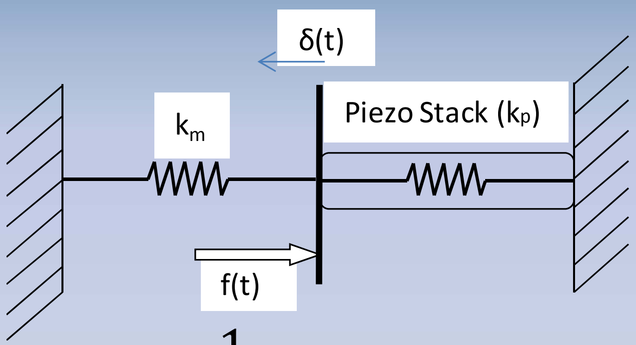
$$F_b = k_p \cdot b \cdot V$$

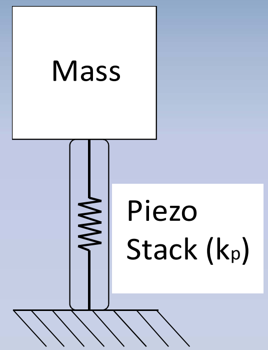
$$F_{ext} = F_b - k_p \cdot \delta$$



Piezoelectrical Behaviour

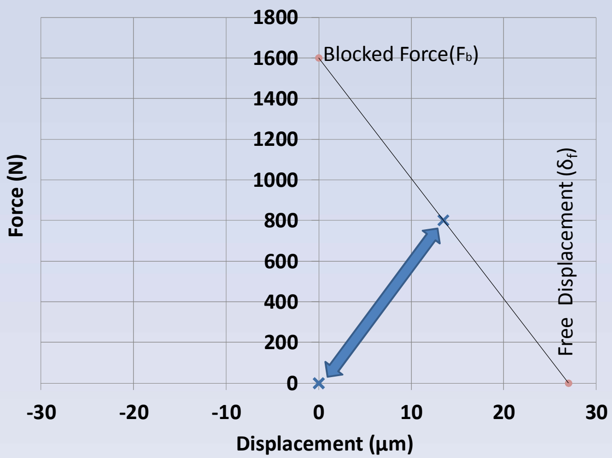
$$F_{ext} = F_b - k_p \cdot \delta$$

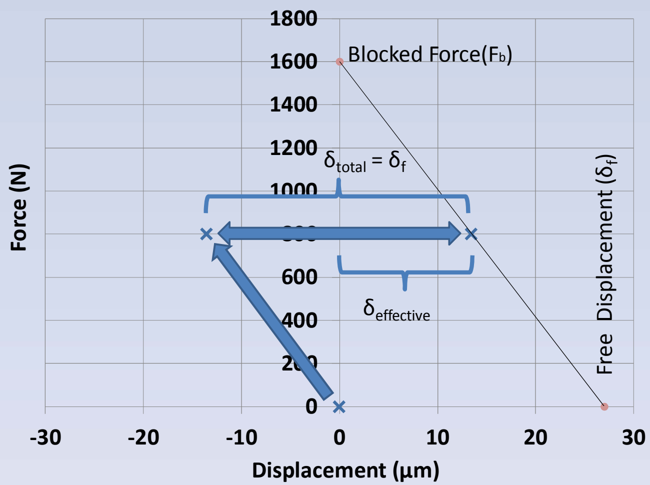




$$\delta = \frac{1}{1+r} \cdot \delta_{free} \qquad r = \frac{k_m}{k_p}$$

Giurgiutiu, V., & Rogers, C. A. (1997). Power and Energy Characteristics of Solid-State Induced-Strain Actuators for Static and Dynamic Applications. Journal of Intelligent Material Systems and Structures, 8(9), 738–750.

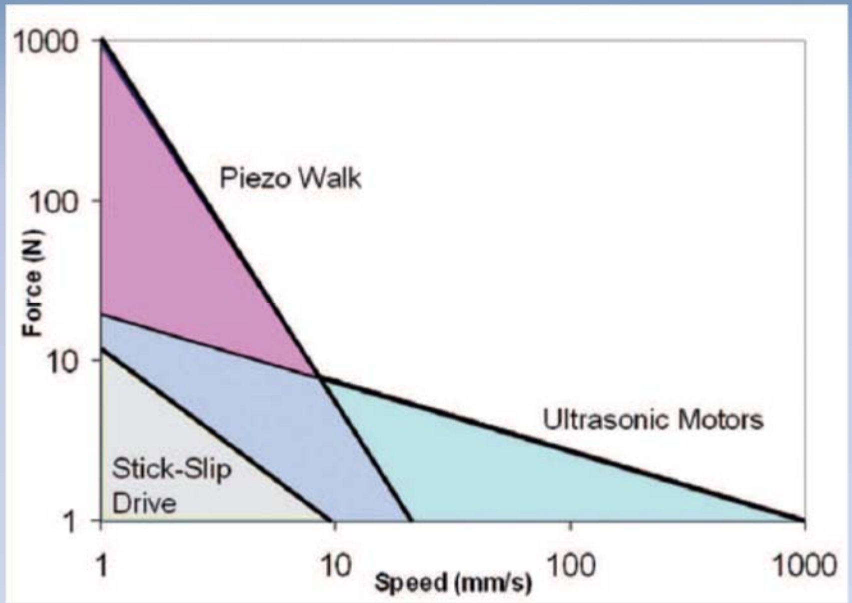




About Piezoelectrical Actuators

Piezo actuators offer some unique advantages:

- Sub-micrometre resolution.
- Large force generation (high force density).
- Sub-millisecond response.
- No magnetic fields.
- Extremely low steady state power consumption.
- No wear and tear.
- Vacuum and clean room compatibility.
- Holding function without significant power consumption.



Speed and force characteristics of piezo motors.
(Spanner, K., & Koc, B. (2010). An Overview of Piezoelectric Motors. *12th International Conference on New Actuators)*

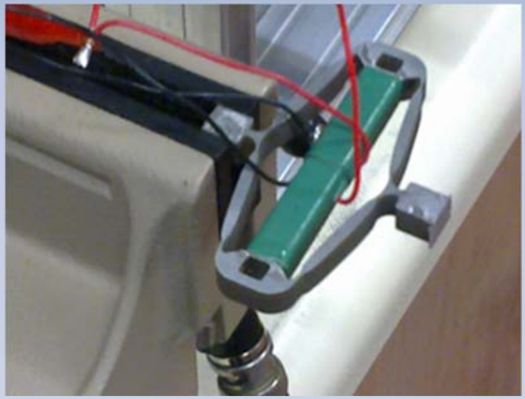
There are also some disadvantages:

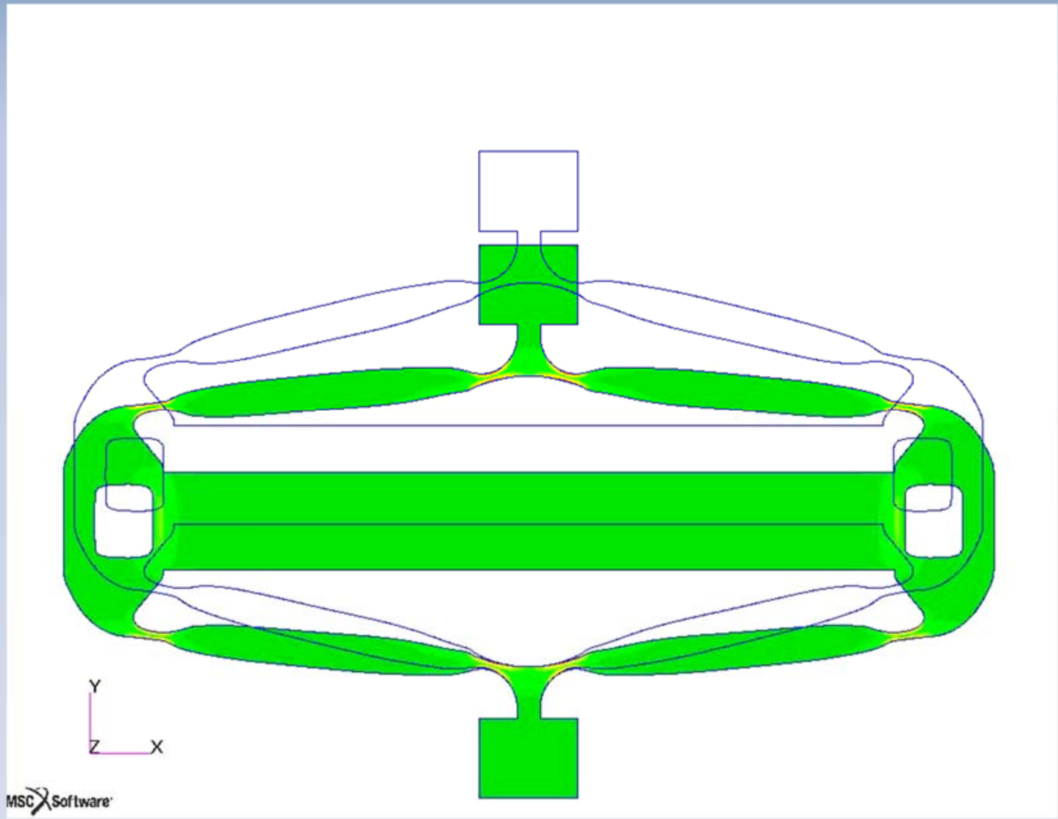
- Highly nonlinear input/output behaviour - Hysteresis.
- Very small motion range.
- Relatively complex electronic controllers are required.

Piezoelectrical Actuators

- Example of a piezoelectrical actuator

A flextensional or Moonie actuator



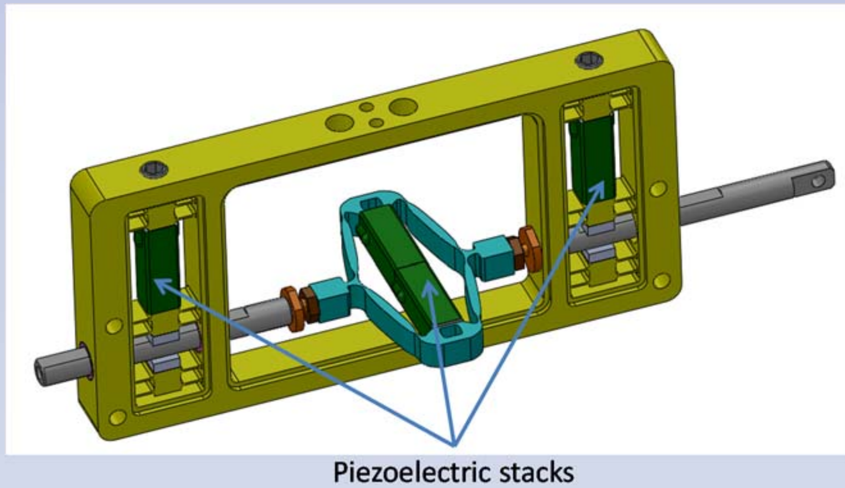


(Newnham, R. E., Dogan, a., Xu, Q. C., Onitsuka, K., Tressler, J., & Yoshikawa, S. (1993). Flextensional “moonie” actuators. Proceedings of IEEE Ultrasonics Symposium.)

Blocked force	160.9 N
Free displacement	231 µm
Maximum stress (free displacement)	233 MPa
Maximum stress (blocked)	559 MPa
Stiffness in actuating direction	694.4 N/mm
Amplification (mechanical)	4.278

Introduction to Inchworm motors
- The basic idea

- The high force density and good dynamic properties of piezoelectric material makes it an attractive technology for actuator applications….
- …. but its very small displacement limits its usefulness. To increase the displacement, mechanical amplification may be used by attaching a lever to a piezoelectric actuator…..
- …..this, however, reduces the force capability.
- Another possibility is to use so-called *Frequency Levering* where an actuator is driven dynamically at a high frequency, and displacement per cycle is added over many repetitions without compromising on the force capability.

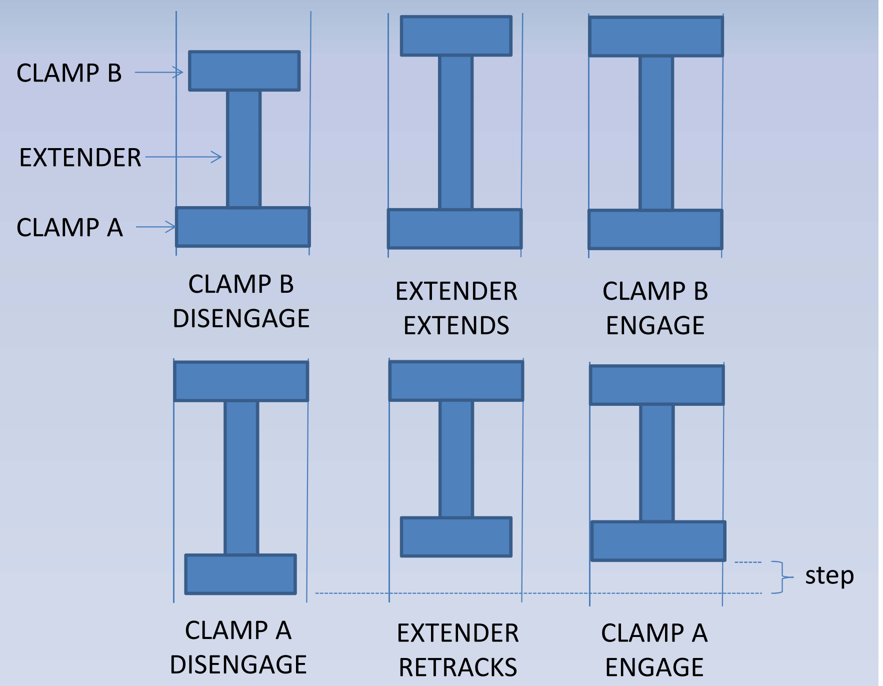


Introduction to Inchworm motors
- The operational principle

Basically, an IWM is three actuators working together. Two of the actuators act as clamps, and the third is an extender mechanism that produces the linear (or rotational) displacement.

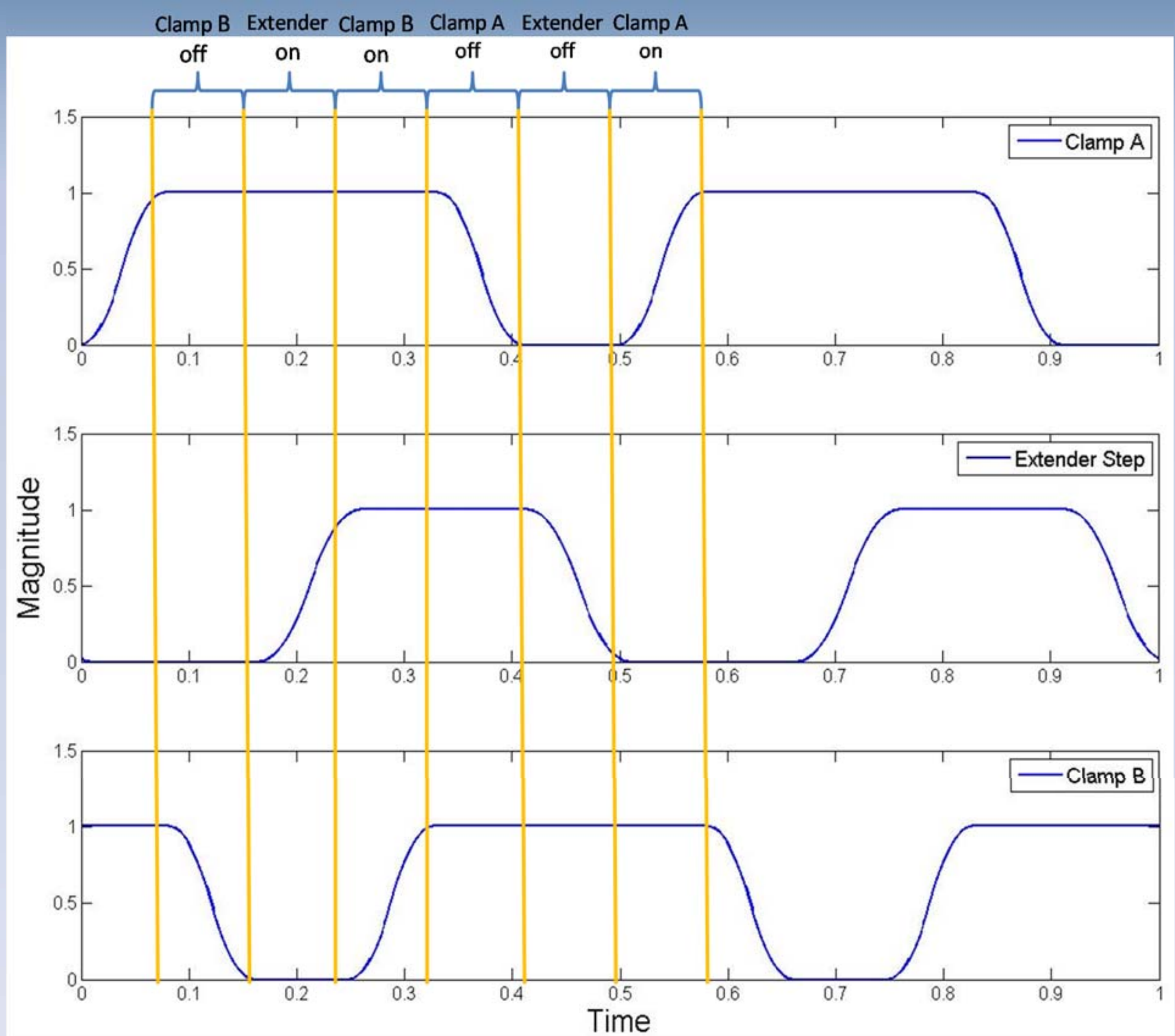
A single operational cycle consists of six steps:

1. Clamp A is activated while clamp B is disengaged.
2. The extender extends.
3. Clamp B is activated. Both clamps are now on.
4. Clamp A relaxes.
5. The extender relaxes / returns to its original shape.
6. Clamp A is engaged.



Introduction to Inchworm motors

- Control signals



Introduction to Inchworm motors
- Application

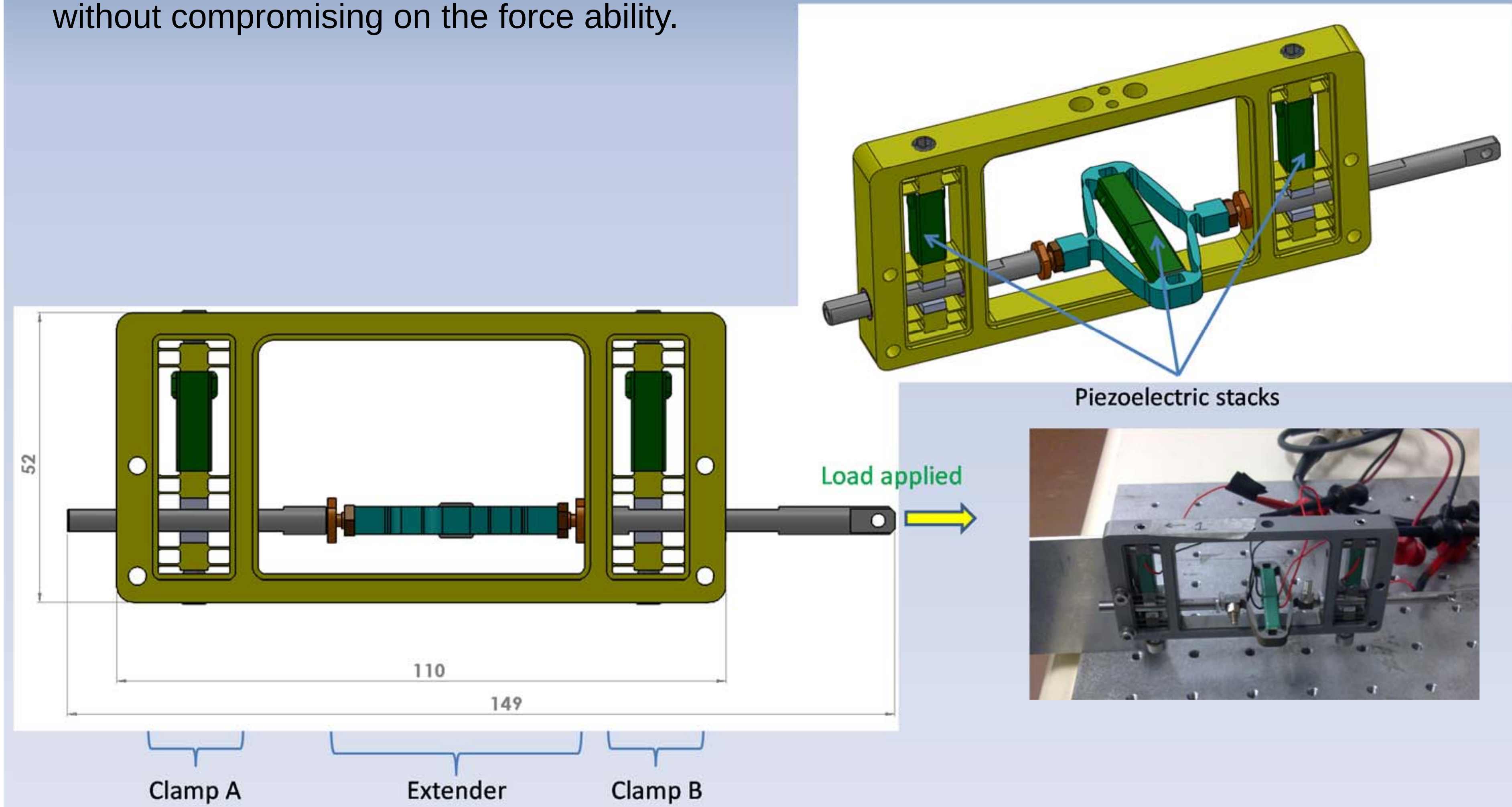
- Piezoelectrical IWM's are well suited to applications requiring moving a relative large load accurately.
- An IWM can hold a large load in position without consuming significant power.
- An IWM can be designed to hold a load in a power-off mode, i.e fail-to-safety.
- An IWM using a switch mode power supply, can be used for energy scares application.

Application examples:

1. A Morphing wing on a UAV.
2. Focus adjustment of a heavy optical element.
3. Manipulating a work piece during machining operations – XY table.

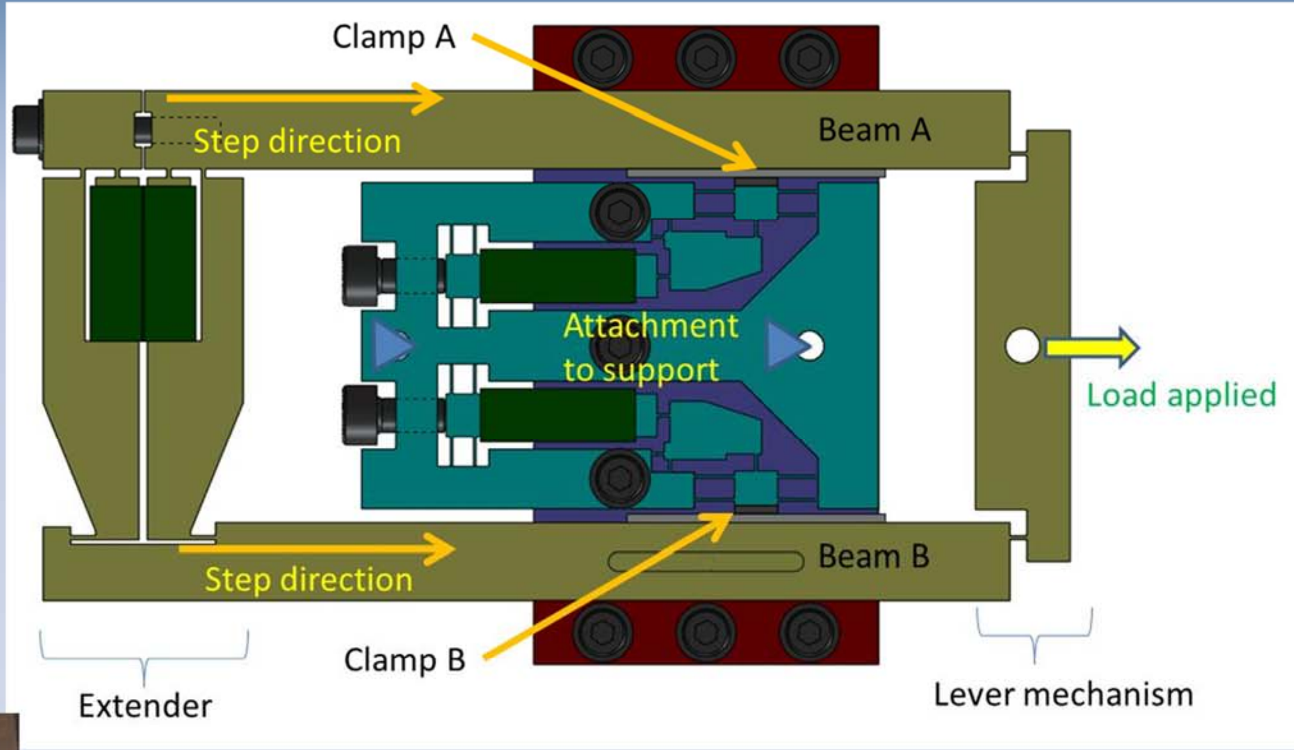
Introduction to Inchworm motors
- The conventional IWM design

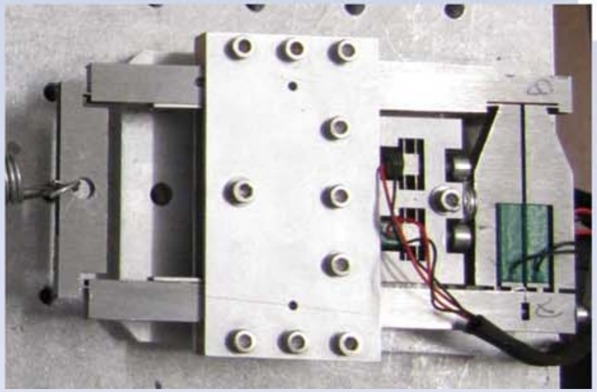
A piezoelectric Inchworm motor accumulates a number of small displacements to obtain large linear displacement without compromising on the force ability.



Introduction to Inchworm motors

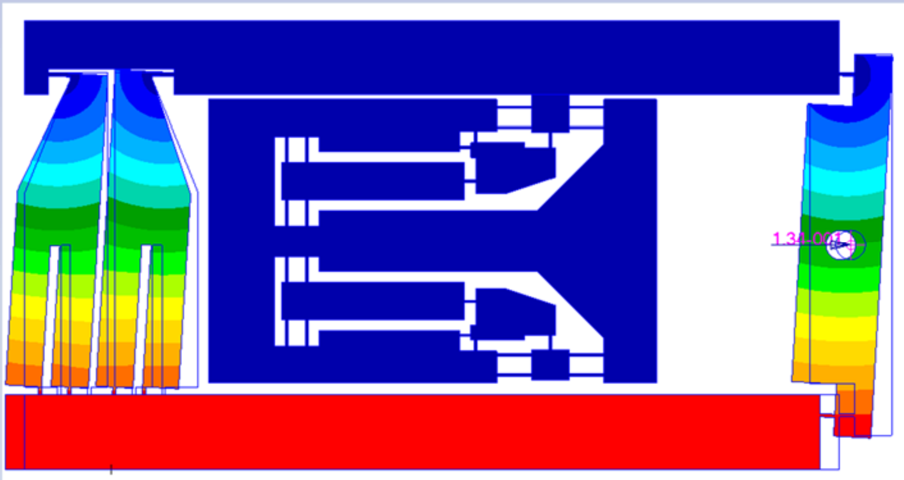
- The IWM design with force duplicator mechanism



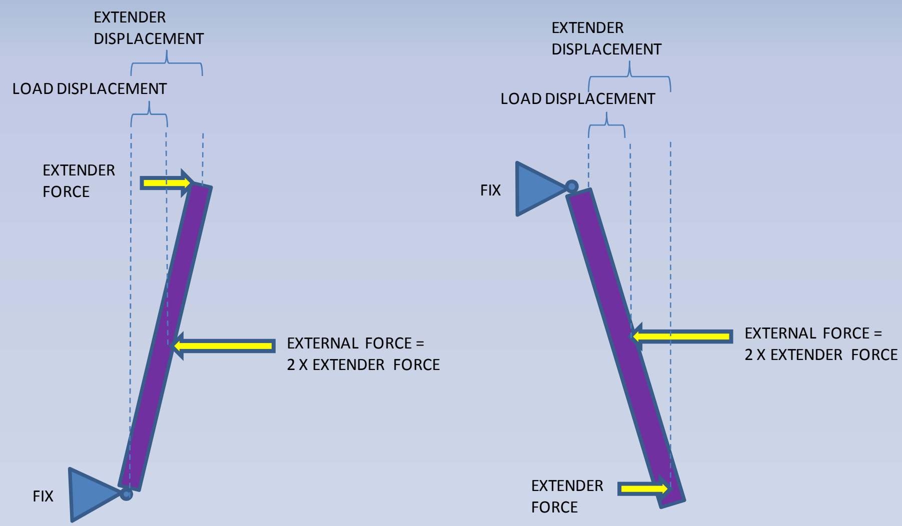


(E. F. Williams and P. W. Loveday, “PIEZOELECTRIC ACTUATION DEVICE,” WO/2013/0728112013.)

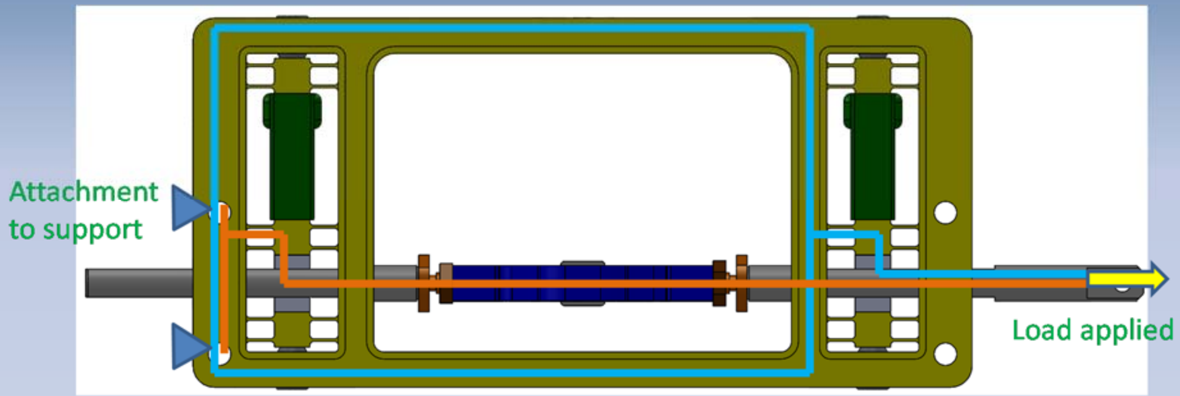
Introduction to Inchworm motors
- The IWM design with force duplicator mechanism

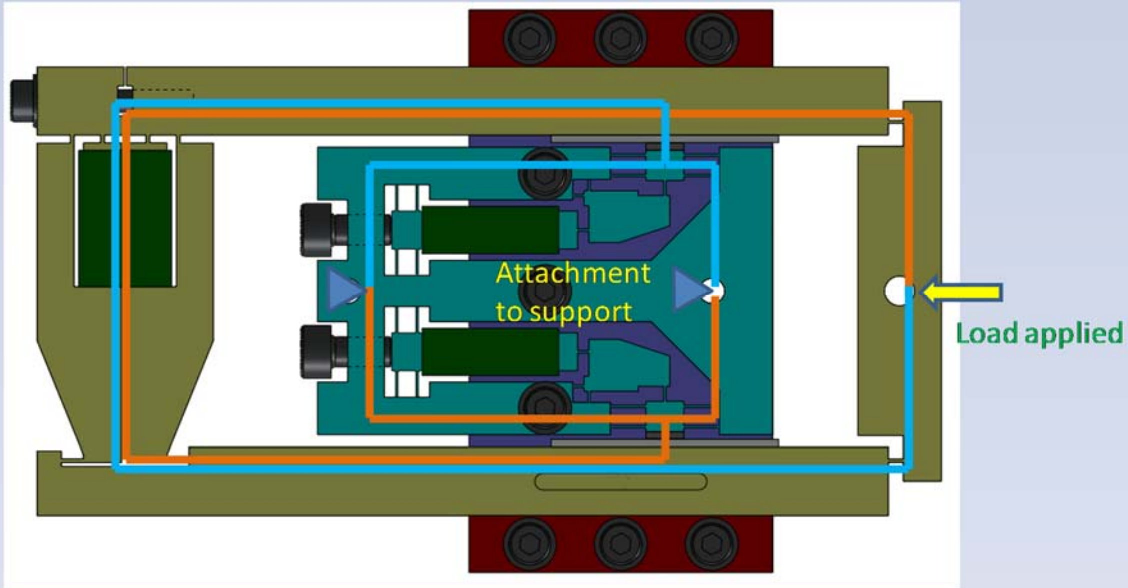


Finite element analysis showing the exaggerated action of the extender and lever mechanism.

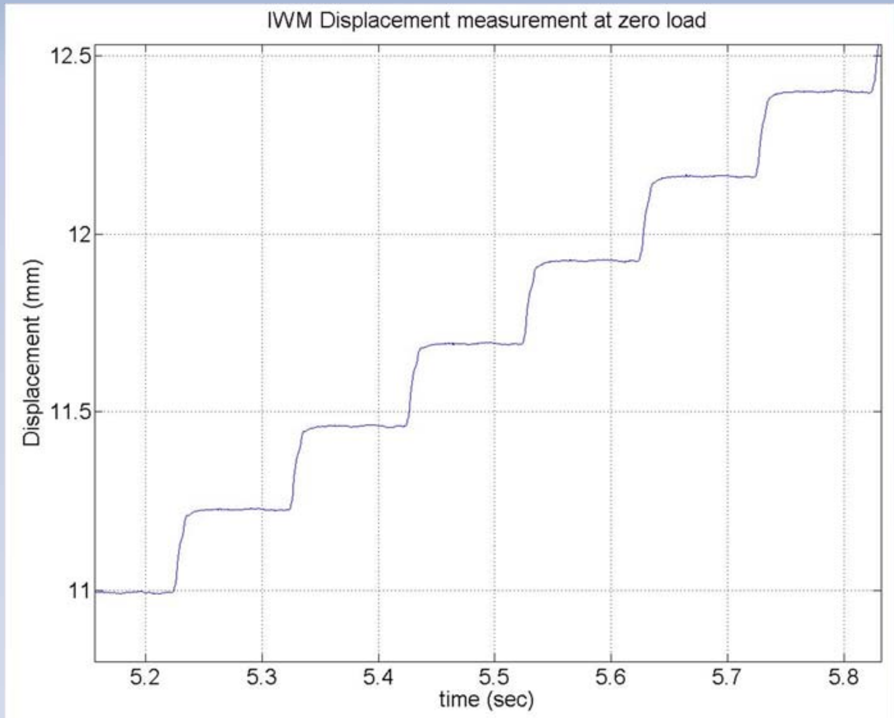


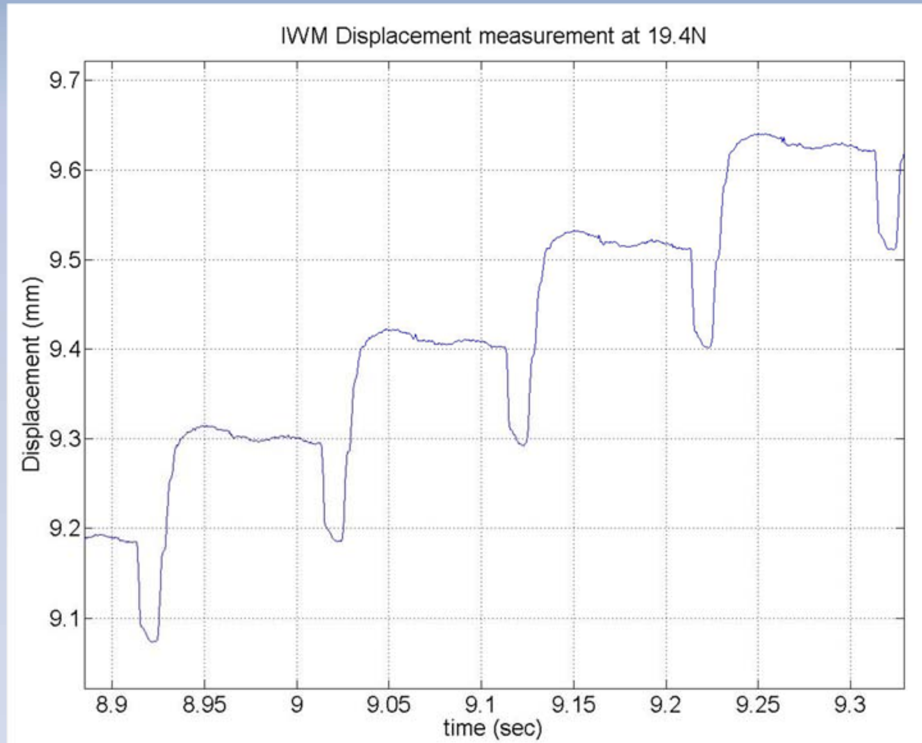
Load limit of an IWM
- Altering load paths



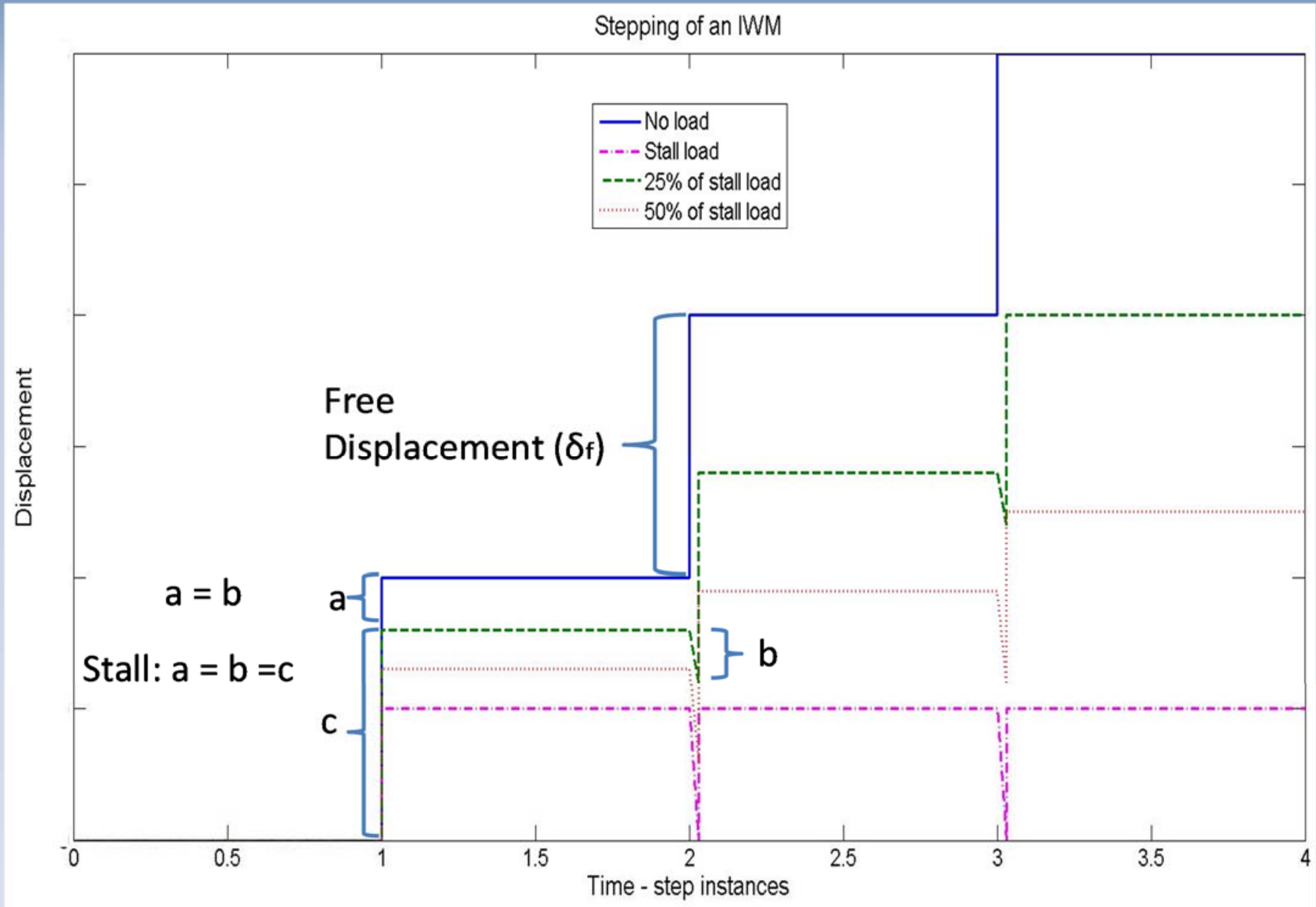


Load limit of an IWM





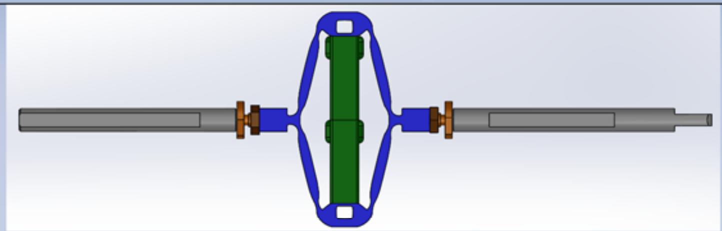
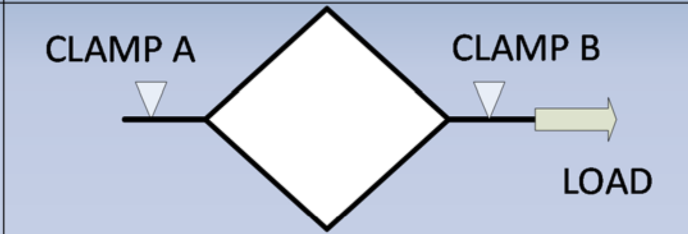
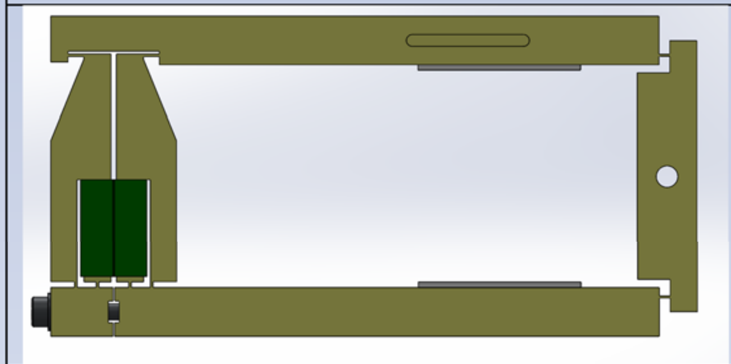
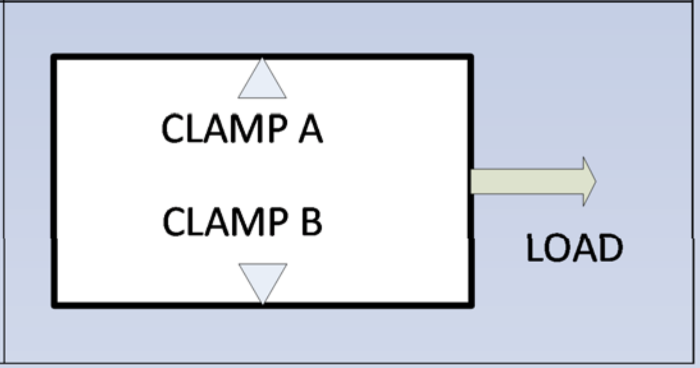
Load limit of an IWM



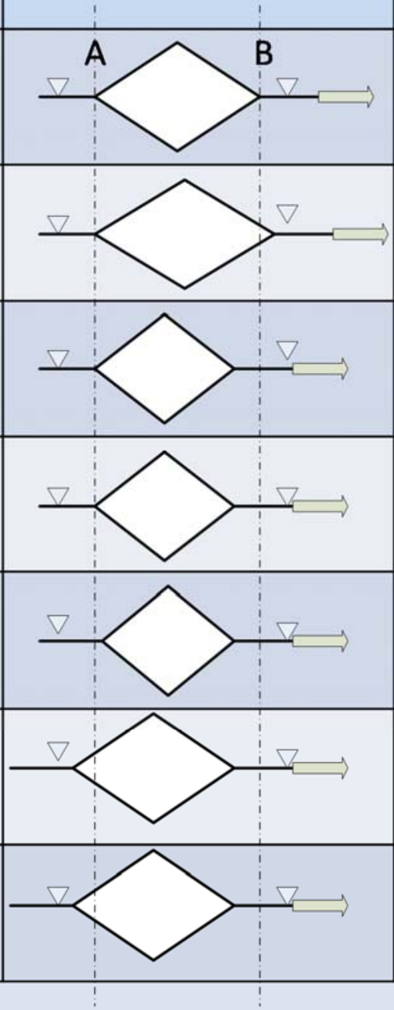
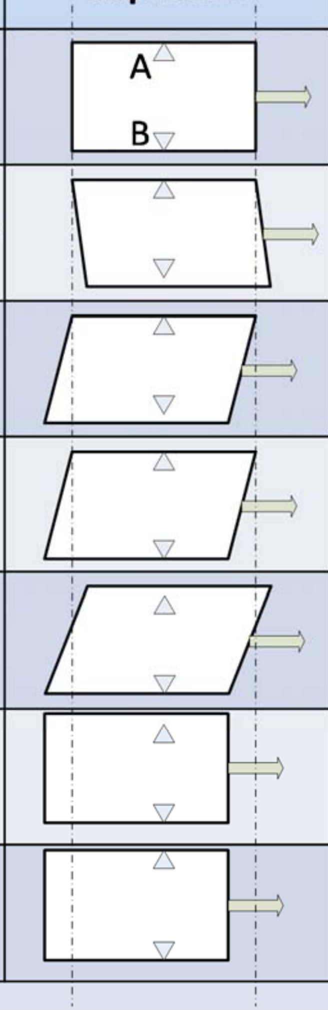
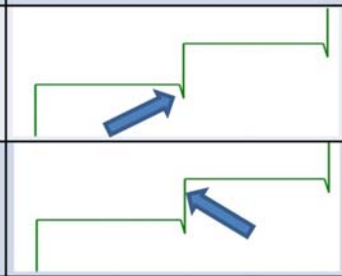
$$\delta_{stall} = \frac{1}{2} \cdot \delta_{free}$$

$$F_L = F_b - k_p \cdot \frac{1}{2} \delta_{free}$$

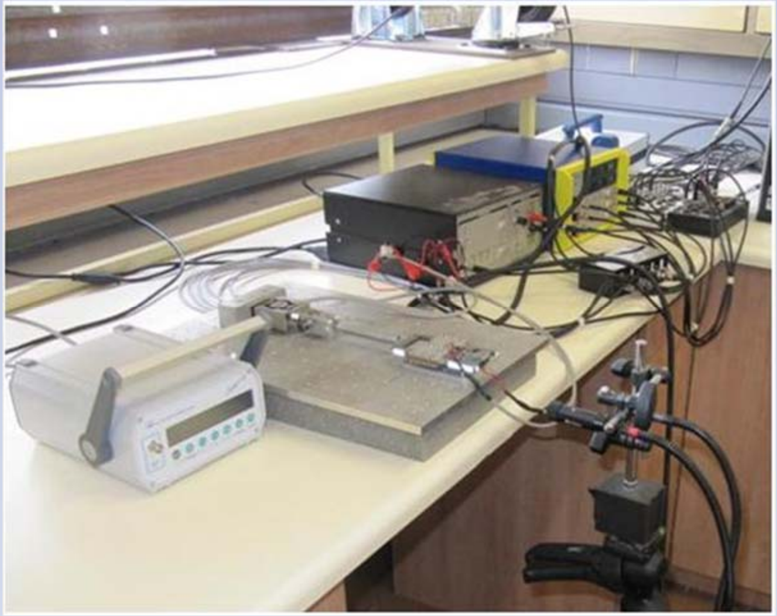
Load limit of an IWM

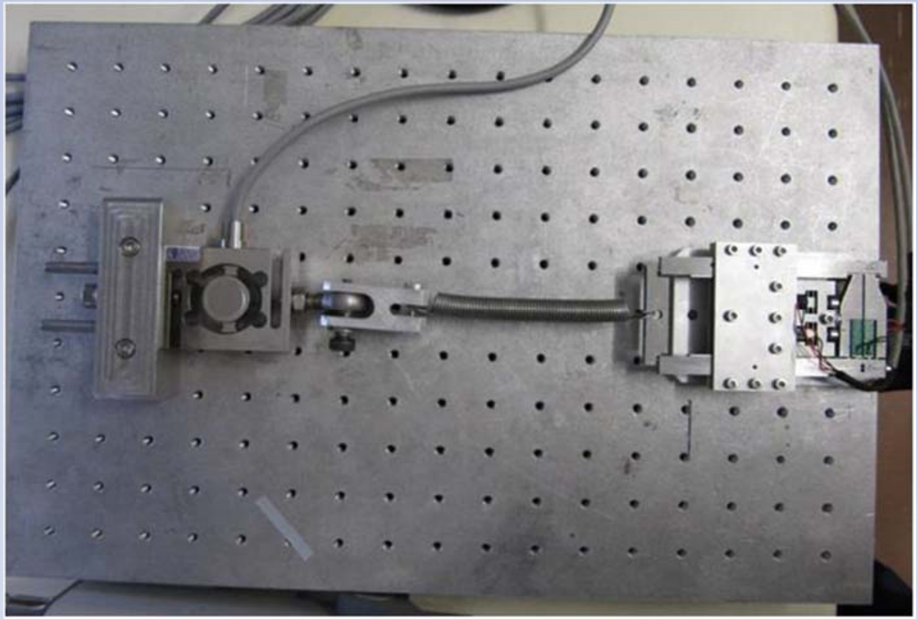
Actual design	Simplified diagram
	
	

Load limit of an IWM

Steps	Conventional IWM	IWM with force duplicator	Snap shot from graph	
START				Start position
1				Clamp A is activated, while clamp B is disengaged. Load results in displacement due to compliance.
2				The extender extends.
3				Clamp B is activated
4				Clamp A relaxes. Load is transferred to 2nd load path. Extender displaces due to compliance..
5				The extender returns to its original shape
6				Clamp A is engaged. A step against the load have been made.

Testing of the IWM

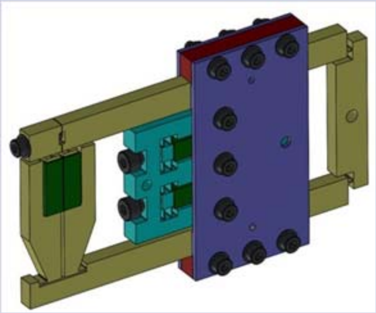




Testing of the IWM

Results for the IWM with force duplicator

	Analysis	Testing
Blocked force	103 N	
Free displacement	134 µm	144 µm
Stiffness of the extender	0.768 N/ µm	0.711 N/ µm – 0.763 N/ µm
Stall load	51.2 *N*	30.5 N



Conclusion

- A new and novel embodiment for a piezoelectric IWM utilizing a beam mechanism has been designed, built and tested.
- A simple method was derived to calculate the stall load of an IWM based on empirical observations.
- Experimental testing showed that this method gave adequate predictions of the stall limit for an IWM for both the conventional design and the IWM with the force duplicator.
- It was observed during testing that the load applied to a IWM reduces the displacement of the extender actuator used in the motor. Further research is required to irrefutably understand this interaction.

Thank you!

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