Nested Dual-chamber Origami (NDO) Actuator with Pressure Compounding and Enhanced Payload

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CONTENTS

Introduction and Background

Stimulus:

Gu, G. et al. *Sci. Robot* (2018)

Electricity

Huang, X. et al. *Adv. Mater* (2019)

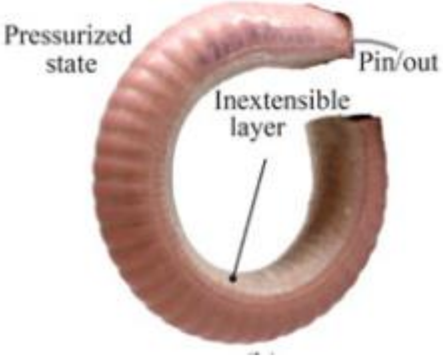
Shape Memory Alloy (SMA)

Liu, S. et al. *IEEE ASME Trans Mechatron.*(2020)

Pneumatics

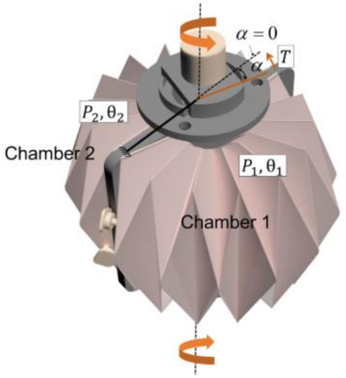
&

Motion forms:



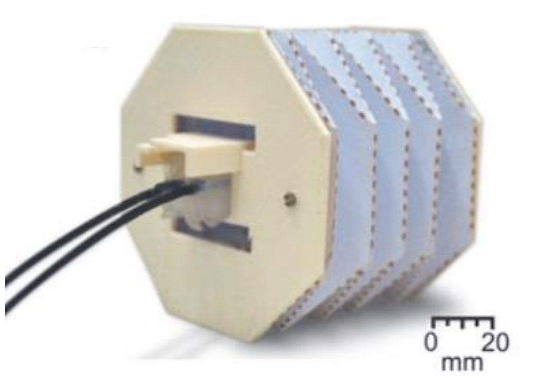
Polygerinos, P. et al. *IEEE Trans. Robot*(2015)

Bending



Yi, J.. et al. *IEEE Trans. Robot*(2019)

Rotation



Paez, L. et al. *SoRo* (2016)

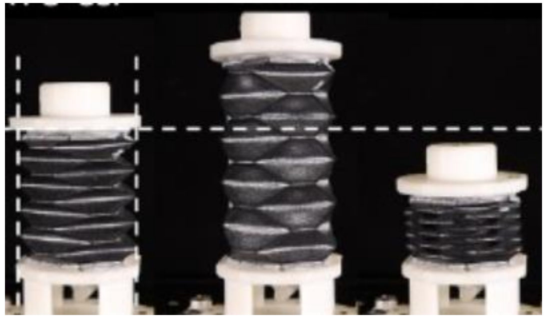
Linearity

Introduction and Background

Robertson, M. et al. *SoRo* (2016)

Yi, J. et al. *SoRo* (2018)

Dong, X. et al. *IEEE Robot Autom Lett.*(2021)



Liu, S. et al. *Chem. Eng. J.*(2024)

Limitations:

~~High bidirectional payload~~ !

- Negative pressure < 1 atm
- Buckling in the thin-walled structure

In this work

To get large bidirectional payload

↓

Nested Dual-chamber Origami (NDO) structure & Compounding of Positive and Negative Pressure Actuation method

↓

NDO actuator prototype

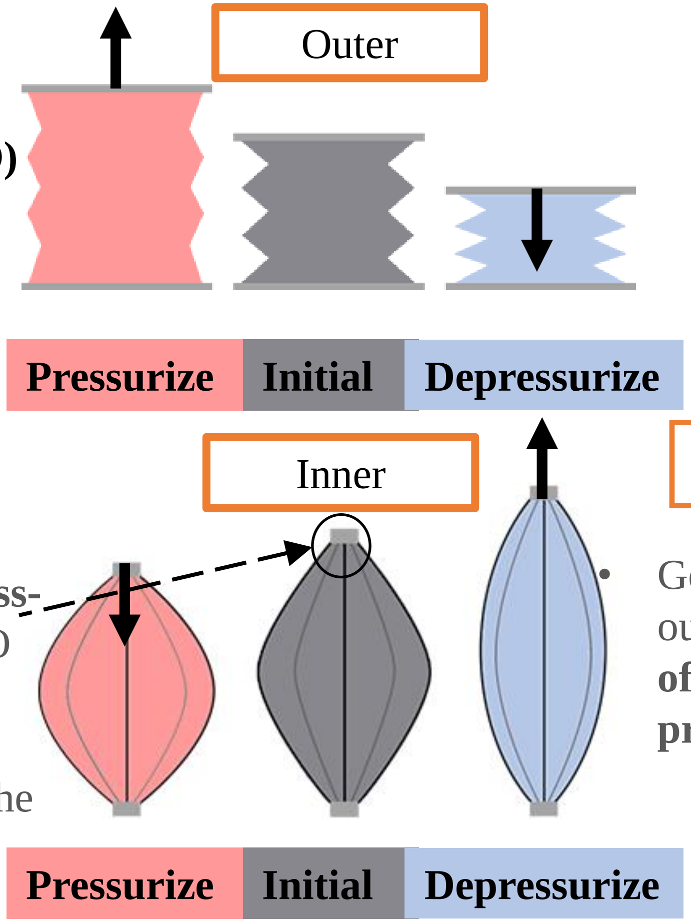
↓

Experiments & validation

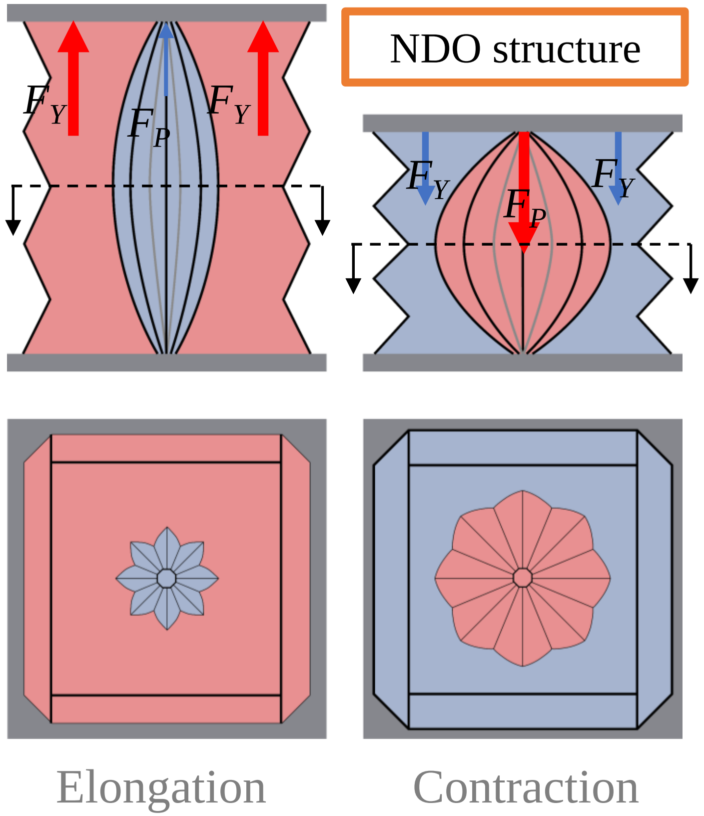
Concept of Nested Dual-chamber Origami (NDO)

Yoshimura Origami (YO)
- Nearly constant inner **radial** dimension

Pleated Origami (PO)
- **Little** impact on the **cross-sectional area** of the YO chamber
- Possible to decouple the mechanical analysis of the two structures



- Generate **bidirectional** output under **compounding of positive and negative pressure actuation**



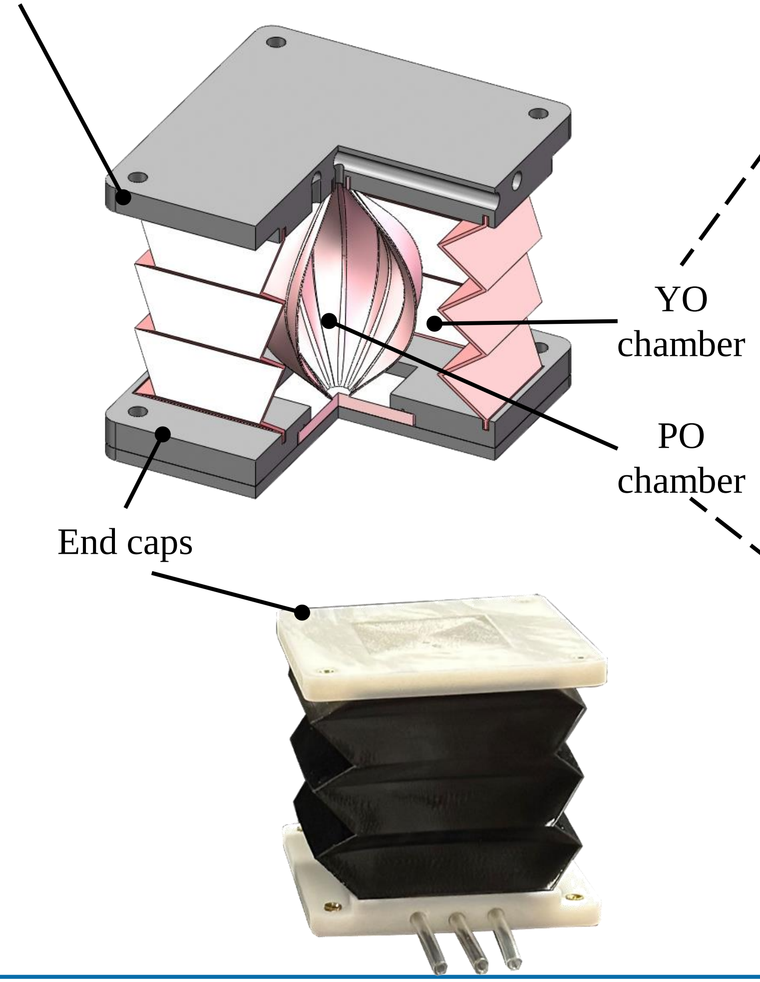
Actuation： Negative pressure OR Positive pressure

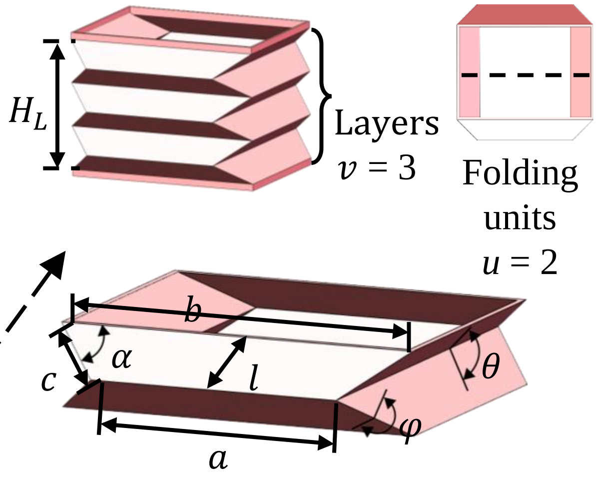
Actuation： Negative pressure AND Positive pressure

Design and Fabrication

End caps:

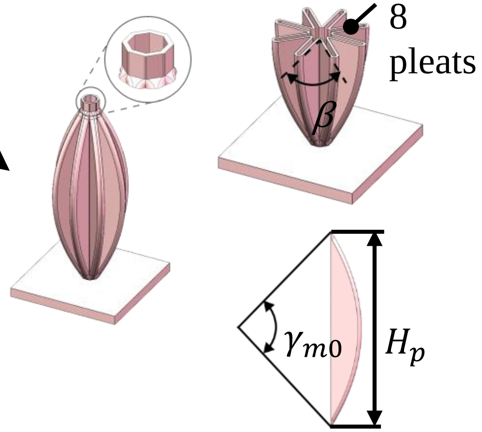
- Photosensitive resin (SLA)
- Embed air channels





Yoshimura Origami

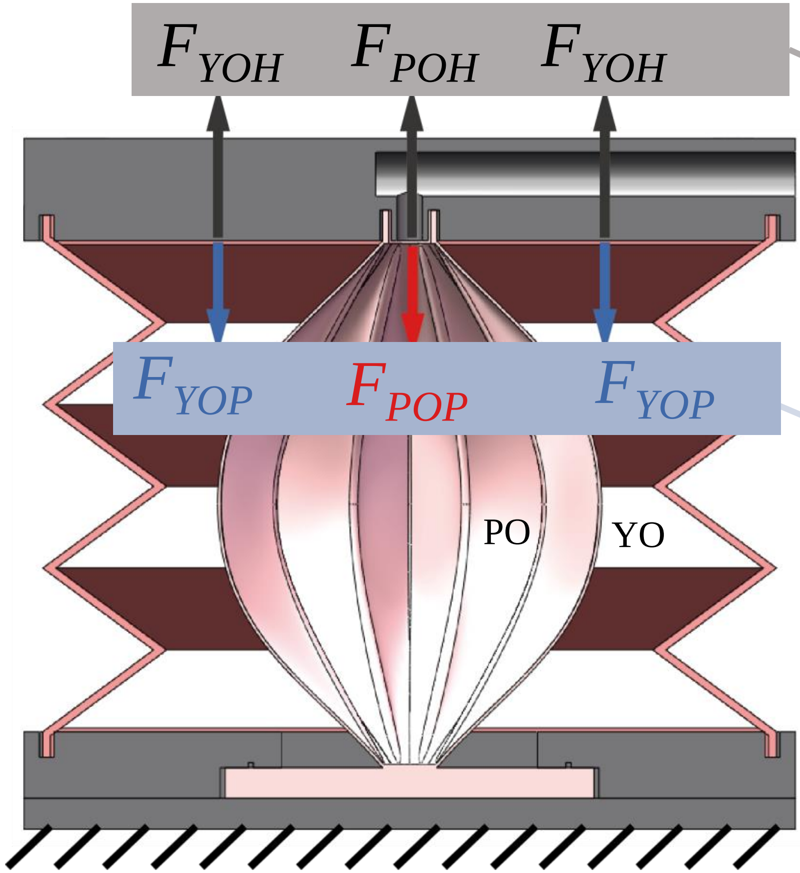
- TPU 95 A (FDM)
- Thickness 0.75 mm
- 3 identical folding layers
- 2 same folding units each layer



Pleated Origami

- TPU 95 A (FDM)
- Thickness 0.6 mm
- 8 same pleats

Modeling of NDO Actuator



Contraction state

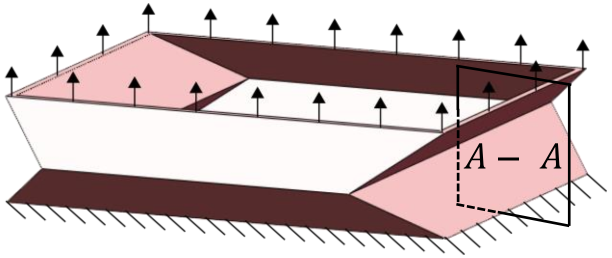
Resisting force: generated by **stiffness** of the chambers

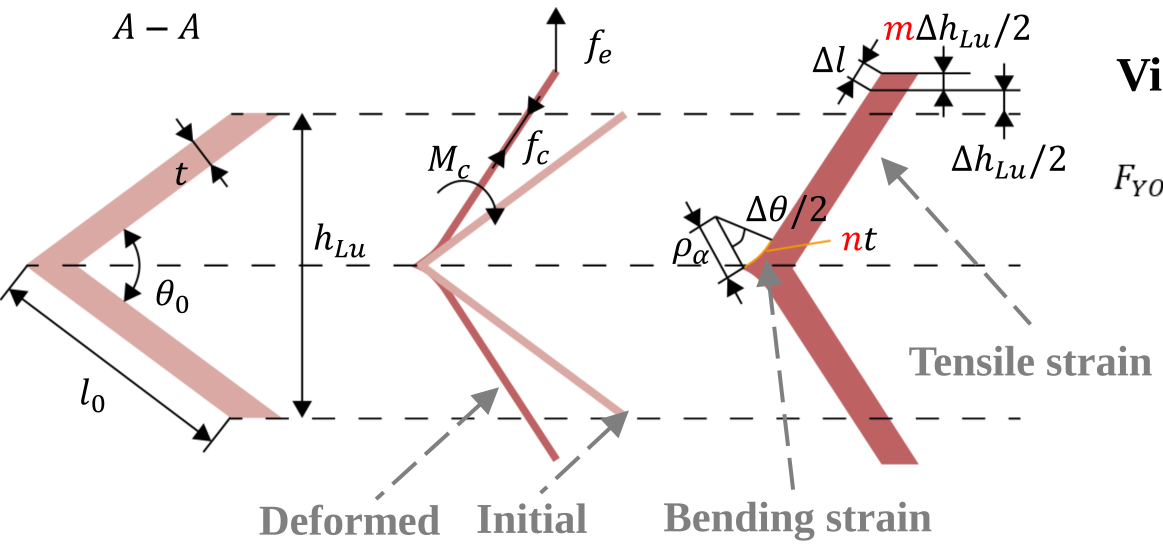
$$F = F_{YO} + F_{PO} = \underbrace{F_{YOH}(H_Y)}_{(A)} + \underbrace{F_{YOP}(P_Y)}_{(B)} + \underbrace{F_{POH}(H_P)}_{(C)} + \underbrace{F_{POP}(P_P)}_{(D)}$$

Driving force: generated by **pressure difference** of the chambers

Modeling of Yoshimura Origami Chamber (outer)

Resisting force analysis:





$$F = F_{YO} + F_{PO} = \underbrace{F_{YOH}(H_Y)}_{(A)} + \underbrace{F_{YOP}(P_Y)}_{(B)} + \underbrace{F_{POH}(H_P)}_{(C)} + \underbrace{F_{POP}(P_P)}_{(D)} \qquad (1)$$

(A) **Resisting force of YO chamber:**

Virtual work: $F_e \cdot dH_Y = \Sigma M_\theta \cdot d\theta + \Sigma M_\varphi \cdot d\varphi + \Sigma f_\theta \cdot dl_\theta$ (2)

Virtual work + Small-strain folding Principle:

$$F_{YOH} = F_e = \frac{uv(a+b)Et^2}{6n(H_Y - H_{Y0})}\left(\arcsin\left(\frac{H_Y}{2vl_0}\right) - \arcsin\left(\frac{H_{Y0}}{2vl_0}\right)\right)^2 + \frac{uvcEt^2}{3n(H_Y - H_{Y0})}\left(\arcsin\left(\frac{H_Y}{tan\alpha\sqrt{4v^2c^2 - H_Y^2}}\right) - \arcsin\left(\frac{H_Y}{tan\alpha\sqrt{4v^2c^2 - H_{Y0}^2}}\right)\right)^2 + \frac{2uvEt(a+b)l_0}{H_Y - H_{Y0}}\left(m - \frac{mH_{Y0}}{H_Y} - ln\left(1 + m - \frac{mH_{Y0}}{H_Y}\right)\right) \qquad (3)$$

(B) **Driving force:** $F_{YOP} = SP_Y$ (4)

Experiments & Validation

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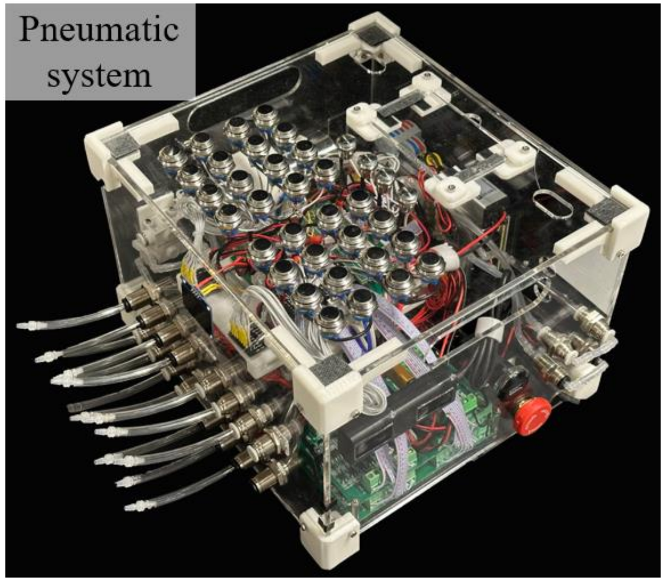
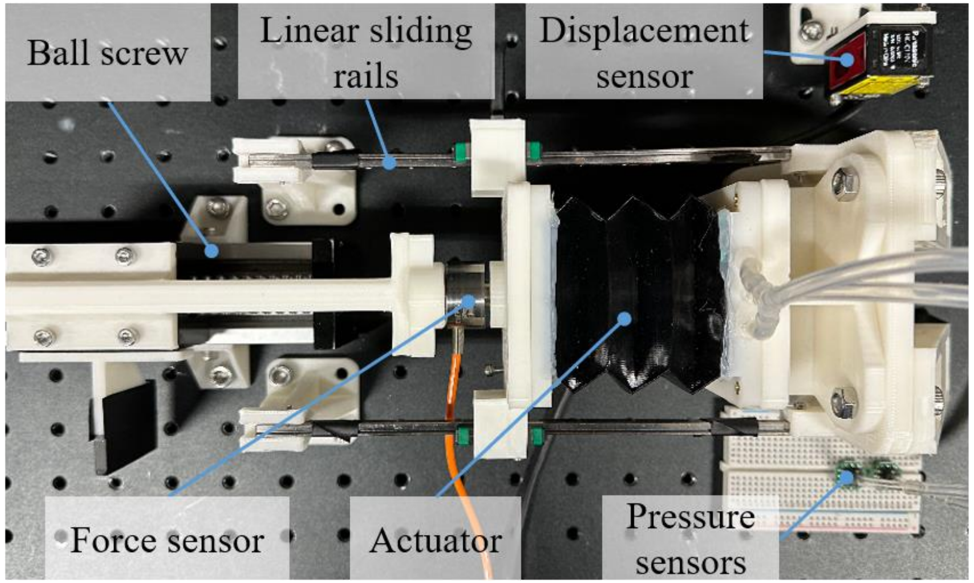
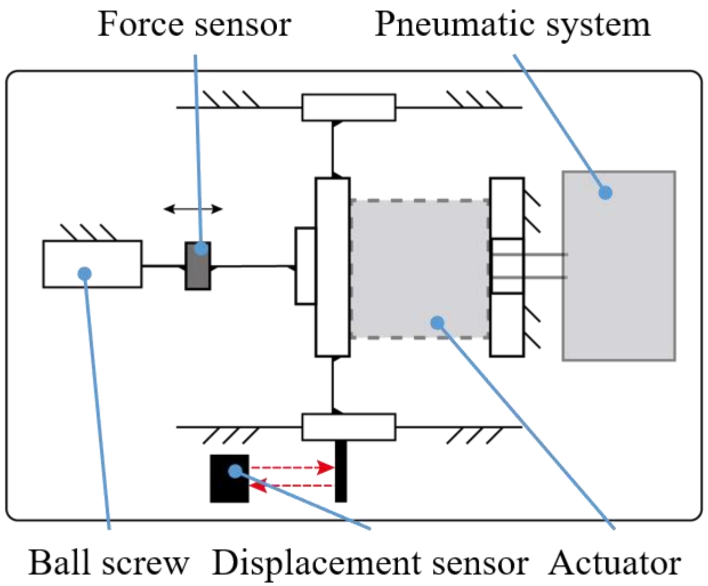
Explore the **mechanical properties** of the mentioned actuators and **validate the effectiveness** of the NDO structure

Experimental setup:







Passive test: Deformed by input force (ball screw)

Active test: Deformed by air supply (pneumatic system)

Test of Yoshimura Origami Chamber (outer)

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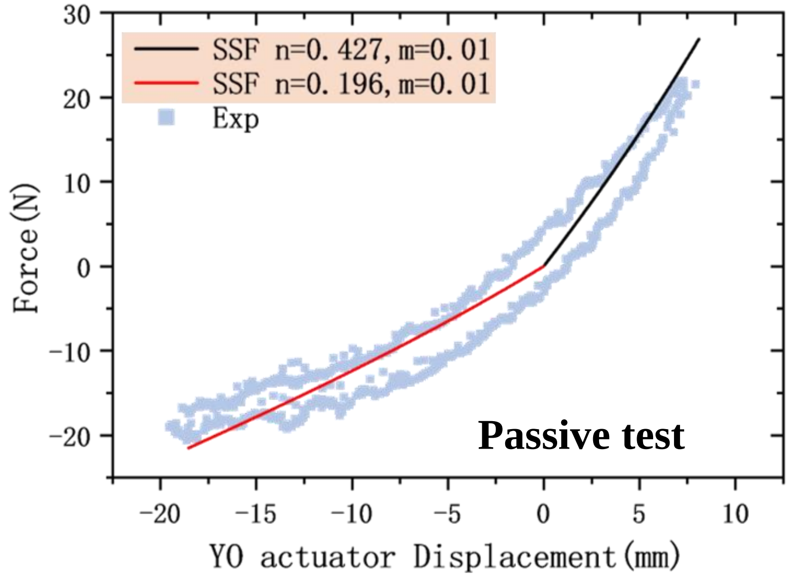

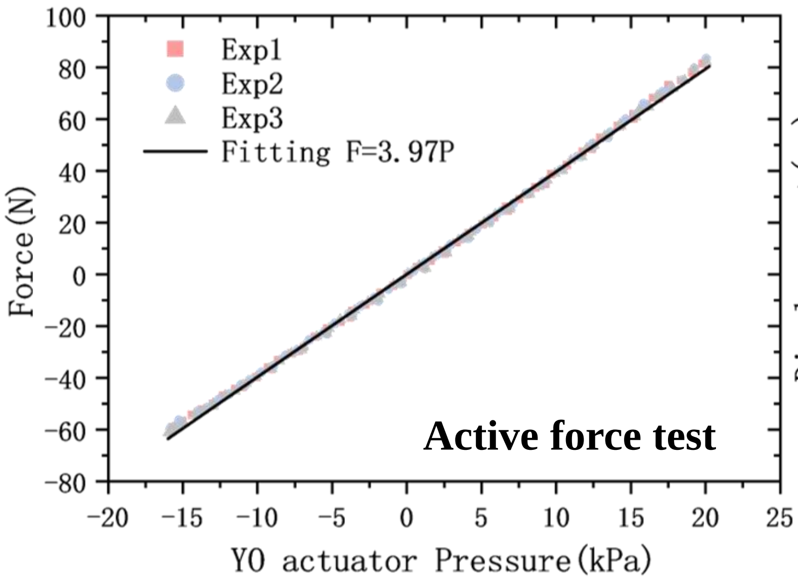

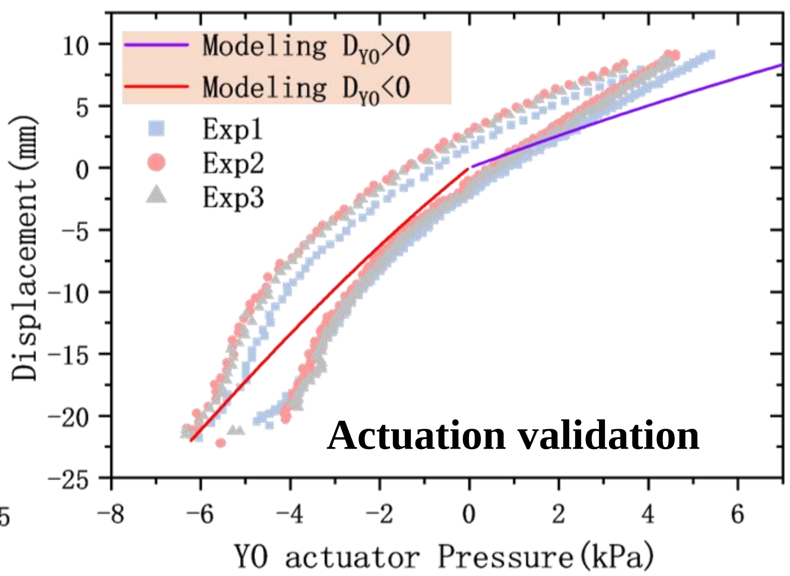

$F_{YOH}(H_Y)$

$F_{YOP}(P_Y)$

$F_{YO} = F_{YOH}(H_Y) + F_{YOP}(P_Y)$

Passive test: Calibrating *n* & *m*

- Compression : n=0.196, m=0.01
- Stretching : n=0.427, m=0.01

Bending region n, and stretching extent m

Active test: Calibrating *S*

- S=3.97 e-3m^2

The effective area

The modeling result was consistent with the testing result in the load free state to some extent.

Test of Pleated Origami chamber (inner)

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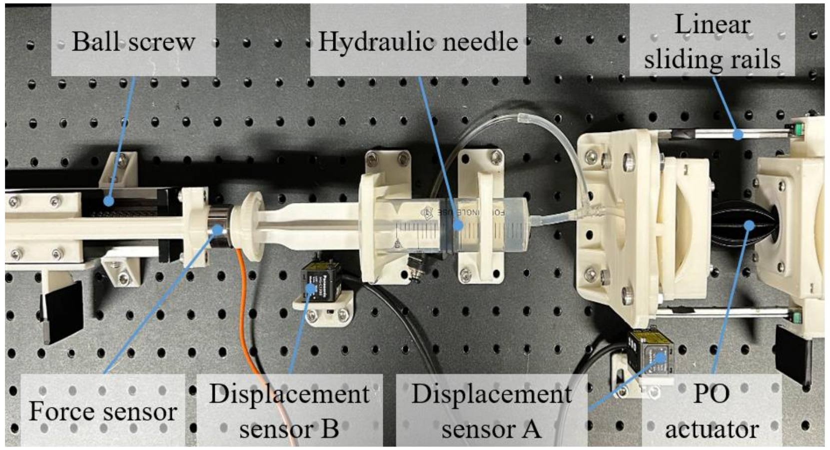
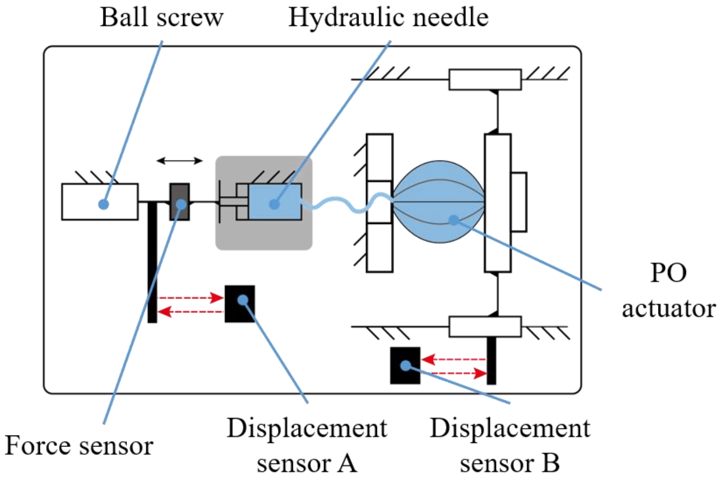
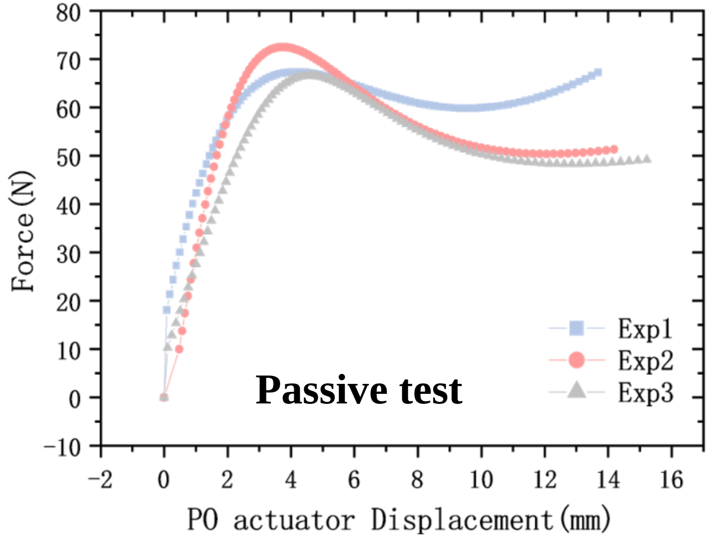




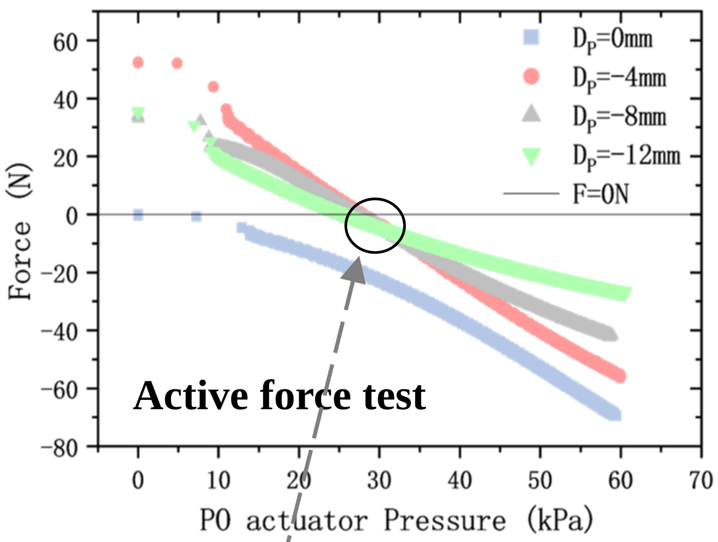
(C) **Resisting force** of PO chamber

Based on the virtual work:

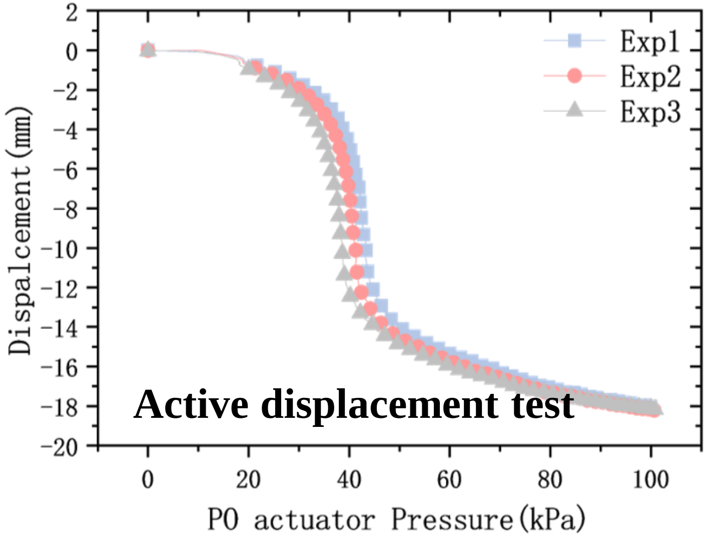
$$F_{POH} = \frac{F_a \cdot dL_b}{dH_P}$$



Resisting force was indirectly calculated by the principle of virtual work



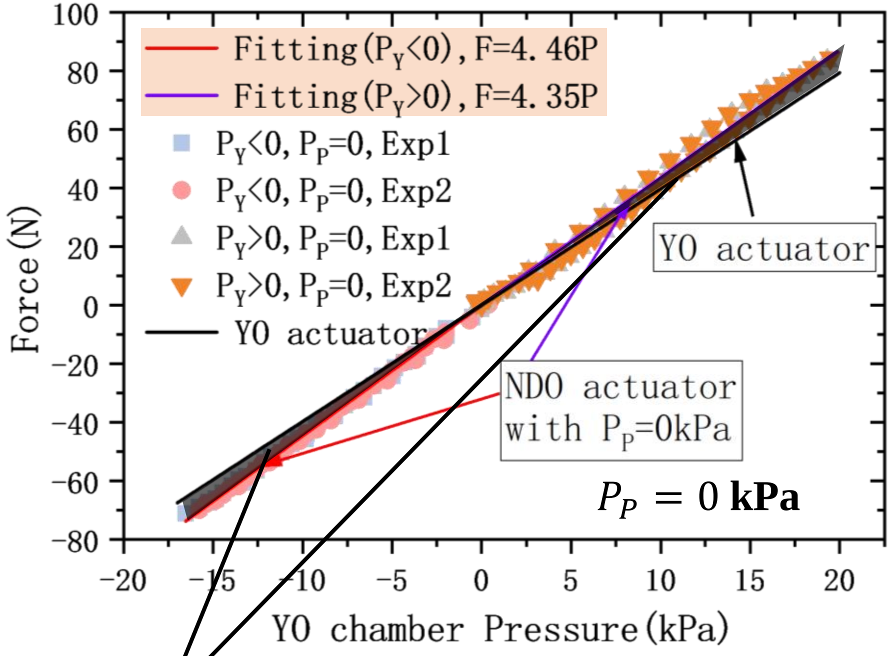
Improvement happened only with a pressure difference over 30kPa

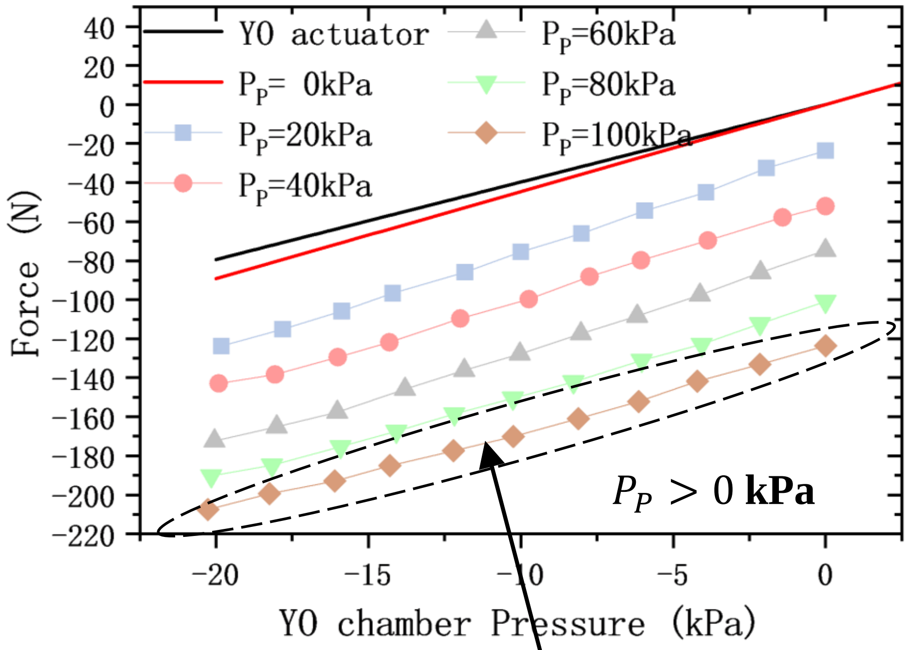


Displacement increased dramatically in the middle stage

Test of NDO & Validation

The minimum pressure of **YO chamber** was **-20kPa** (buckling prevented)





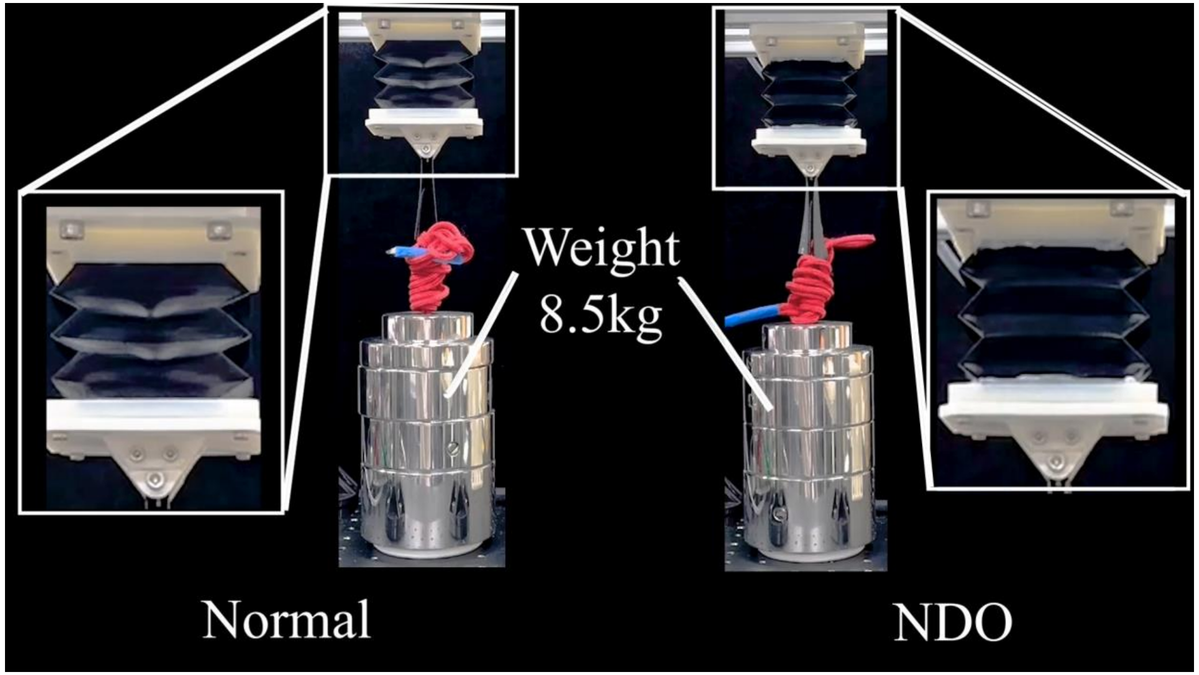
- NDO structure inherently offered an improvement on force:
- **10N (12.5% increase**) in the **contraction** direction ;
- **8N (10% increase**) in the **elongation** direction.

- When the PO chamber was set to 100kPa, it offered an improvement about **130N, (162% increase)** in the contraction direction.

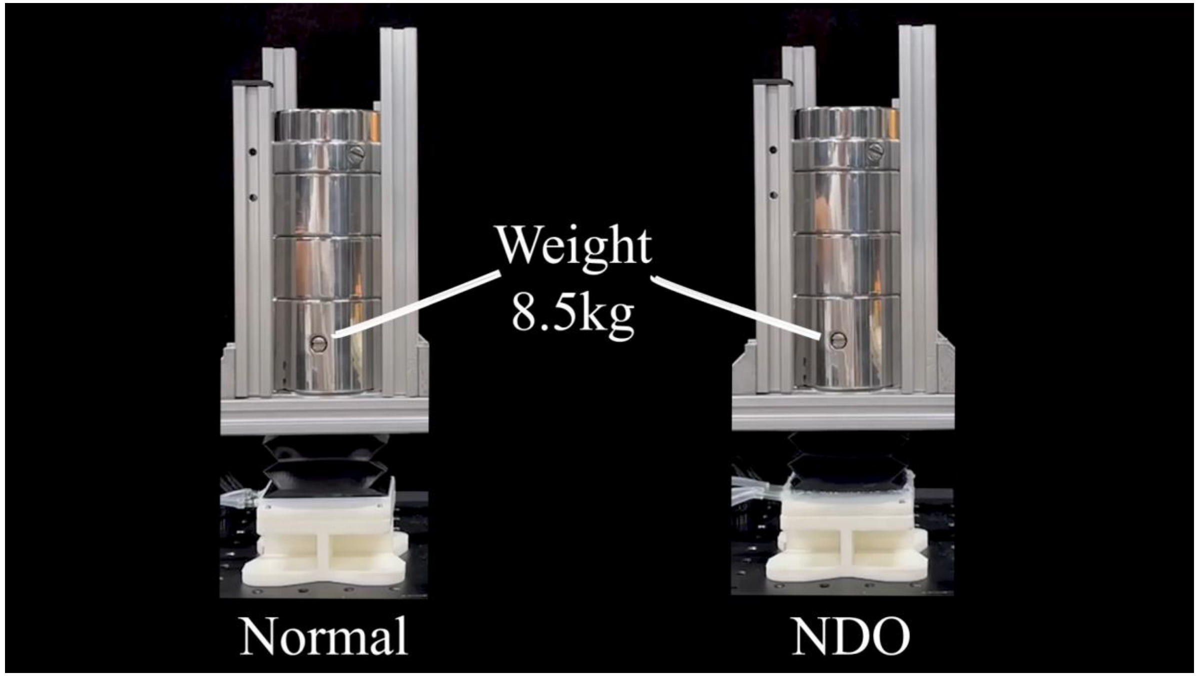
NDO structure can simultaneously offer high bidirectional payload.

Demonstration

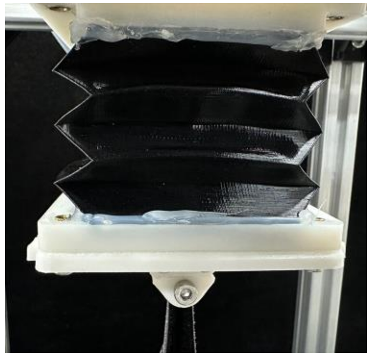
Contraction



Elongation



Buckling



No buckling

- **Avoid buckling** during depressurization
- **High bidirectional payload**

Conclusion & Future Work

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Conclusion:

Concept:

- NDO structure & Compounding actuation for high bidirectional payload

Design & Fabrication:

- A compact NDO actuator prototype was designed and fabricated

Experimental validation:

- Inherently, 10N in the contraction direction (12.5%) and 8N (10%) in the elongation direction
- Based on the NDO design and Compounding actuation, 130N (162%) in the contraction direction

Future work:

Modeling:

- Refining the mechanical model for better actuation

Application:

- More applications to validate the reliability
- Bidirectional payload of motions like twisting and bending

Thanks for Listening!