

Soft Actuators

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Running a laboratory as an associate professor at UEC

Mainly working in the field of soft robotics

新竹研究室
Shintake Research Group
電気通信大学 情報理工学研究科 機械知能システム学専攻
Department of Mechanical and Intelligent Systems Engineering,
University of Electro-Communications

お気軽にお問い合わせください。実験室（東9-409、東4-701）でのラボワークも常時受け付けています。

卒研配属に関する資料は[こちら](#)です。

卒研配属生向け研究室公開を下記の時間帯で行っています。お気軽に訪問ください。

場所：東9-409（実験室）

- 11/1（水）16:00-18:00
- 11/8（水）16:00-18:00
- 11/15（水）16:00-18:00
- 11/22（水）16:00-18:00
- 11/26（訓布祭）11:00-17:00（新竹は出張のため不在です）

他の実験室（東4-701）や学生部屋（東4-330/331）を見学希望の方は、訪問の際にその旨申し出てください。

希望研究室登録前の配属希望面談は別途調整しますので連絡ください。

website: <https://www.shintakelab.net/>



電気通信大学 情報理工学研究科
機械知能システム学専攻



研究室ウェブサイト：
<https://www.shintakelab.net/>
研究テーマ

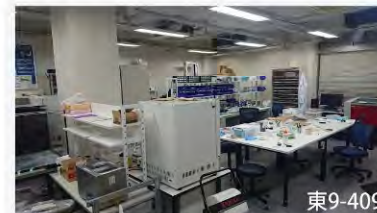
新竹研究室 配属人数：5名

担当教員：新竹 純

連絡先：shintake@uec.ac.jp

柔らかい材料を用いたアクチュエータやセンサ、ロボットの研究開発を行っています。分野としては、ソフトロボティクス、生分解性ロボティクス、生物模倣ロボティクス、および植物ロボティクスです。興味のある方、ぜひ一緒に研究しましょう！より具体的な研究テーマについて知りたい方はお問い合わせください。

研究環境



東9-409



東8-CR

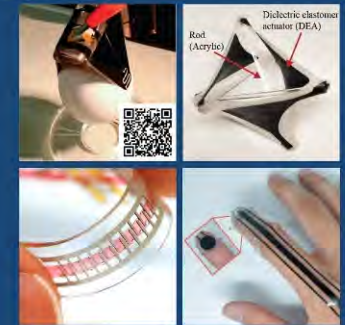


東4-701

加工機や測定装置など、様々な機器を用いて研究を行っています。充実した設備が揃っています。

1. ソフトロボティクス

人工筋肉を用いた柔らかいロボットやアクチュエータ、センサ、ウェアラブルデバイス、およびポンプの開発



2. 生分解性ロボティクス

土に還る環境に優しいロボットの開発



3. 生物模倣ロボティクス

魚やカメなどの様々な水中生物を模倣したロボットの開発



4. 植物ロボティクス

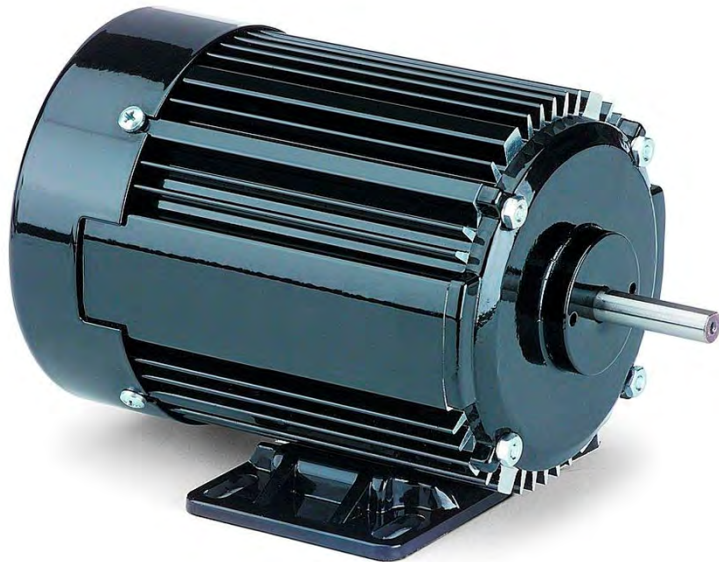
植物の解析とそれに基づく革新的なロボットの開発



国立大学法人
電気通信大学
The University of Electro-Communications

Actuators

- Convert energy into motion that can be used to do work
- Examples:



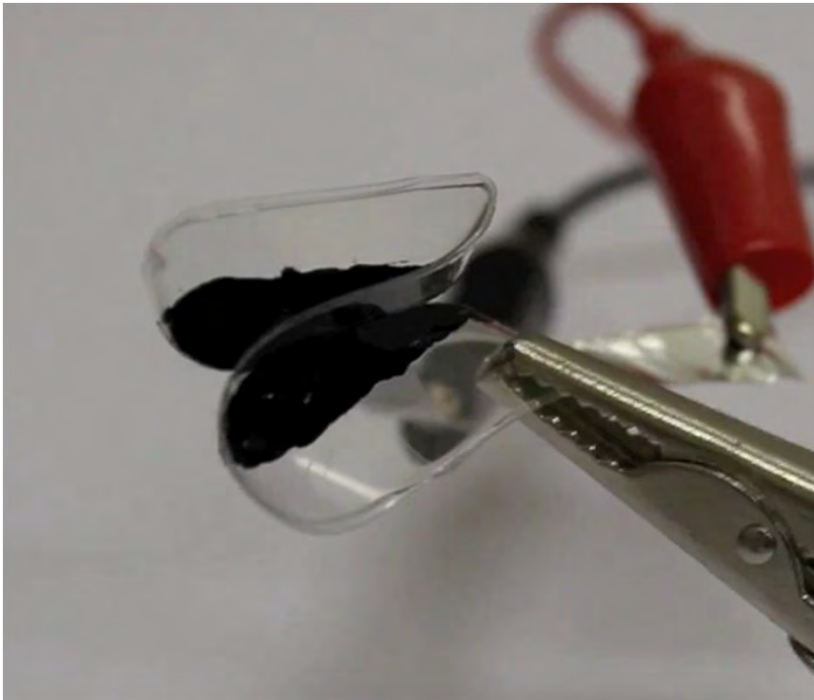
Motor
(directindustry.com)



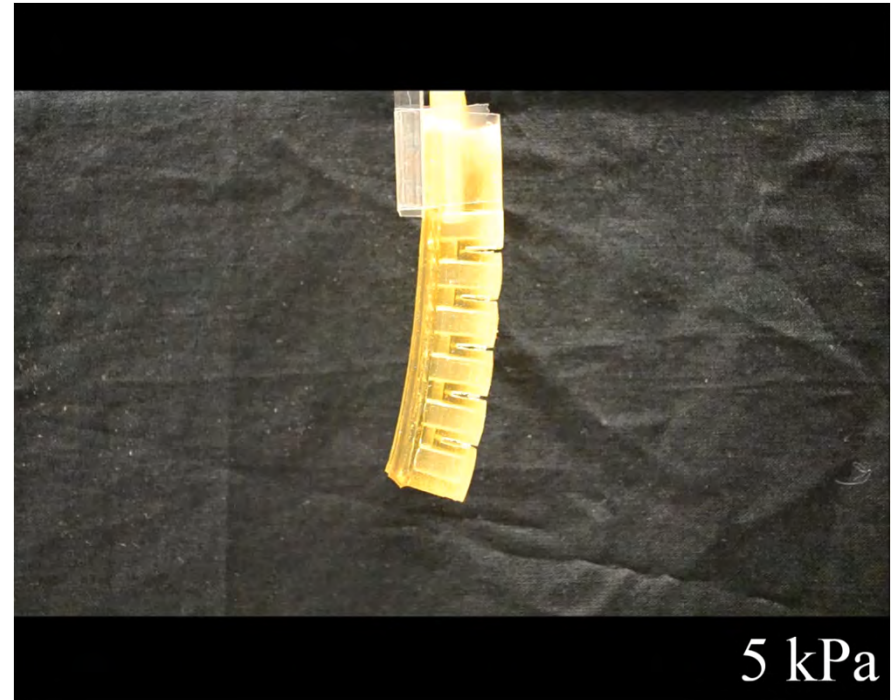
Muscle
(theknowledgepark.blogspot.com)

Soft actuators

- Made of compliant materials
- Materials or compliant structures themselves deform by external stimuli (*stimuli $\approx$ inputs)
- Simpler than conventional rigid actuators
- Often called as Artificial Muscle
- Examples:



Electrical soft actuator



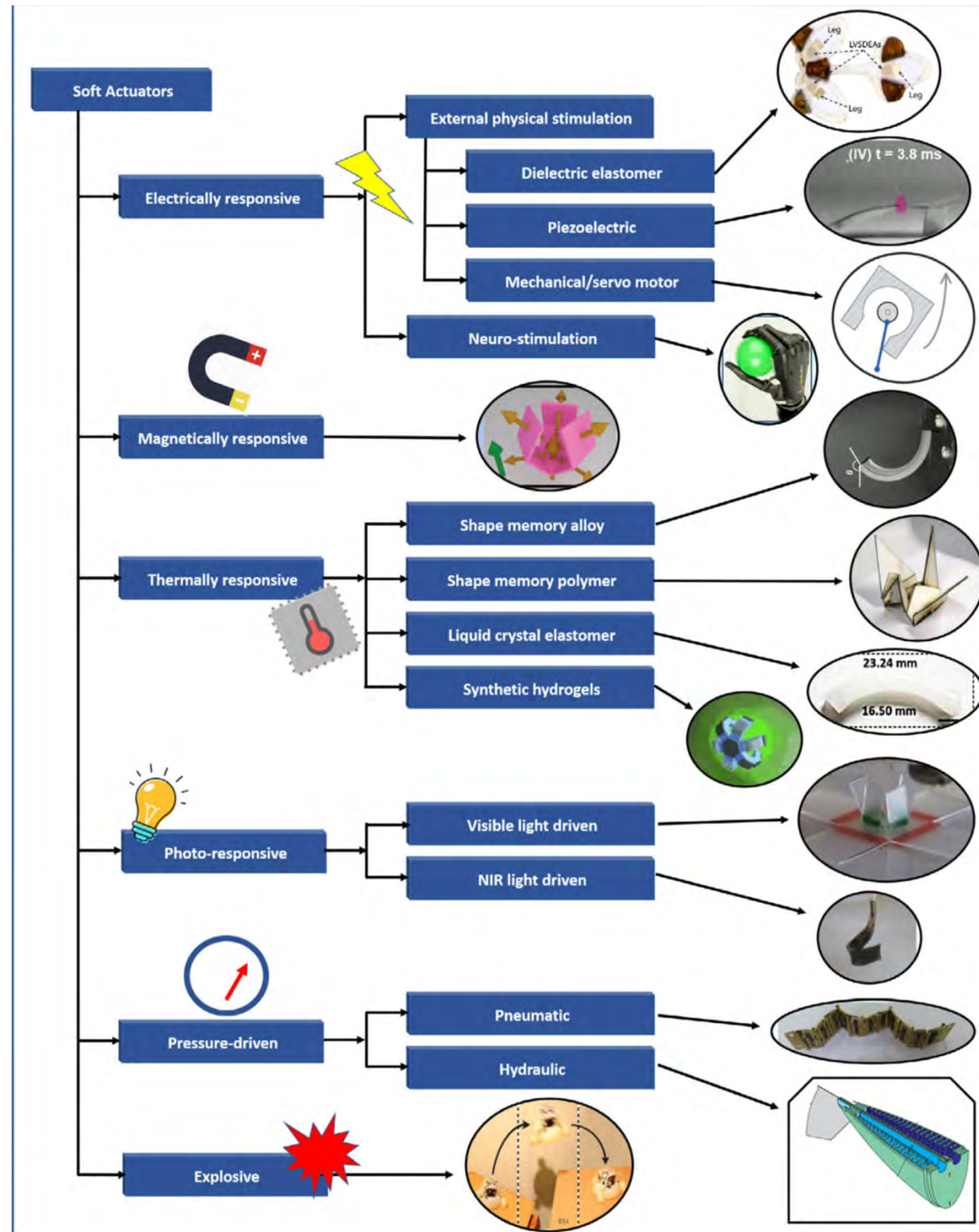
Fluidic soft actuator

Soft actuators

They rely on stimuli of:

- Electric
- Magnetic
- Thermal
- Light
- Pressure

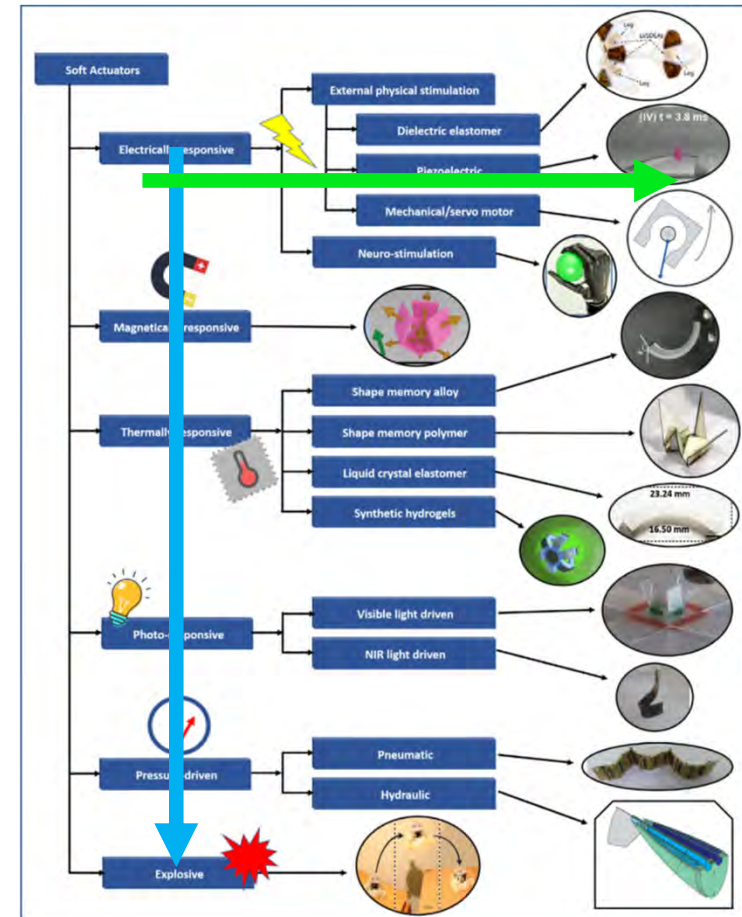
Under which many sub-classes and configurations are being developed.



Aim of the topic “Soft Actuators”

11/14: Detail a single soft actuator technology and describe how it enables various actuator configurations and robotic systems.

11/21: Overview existing soft actuators and discuss their pros and cons, followed by homework.

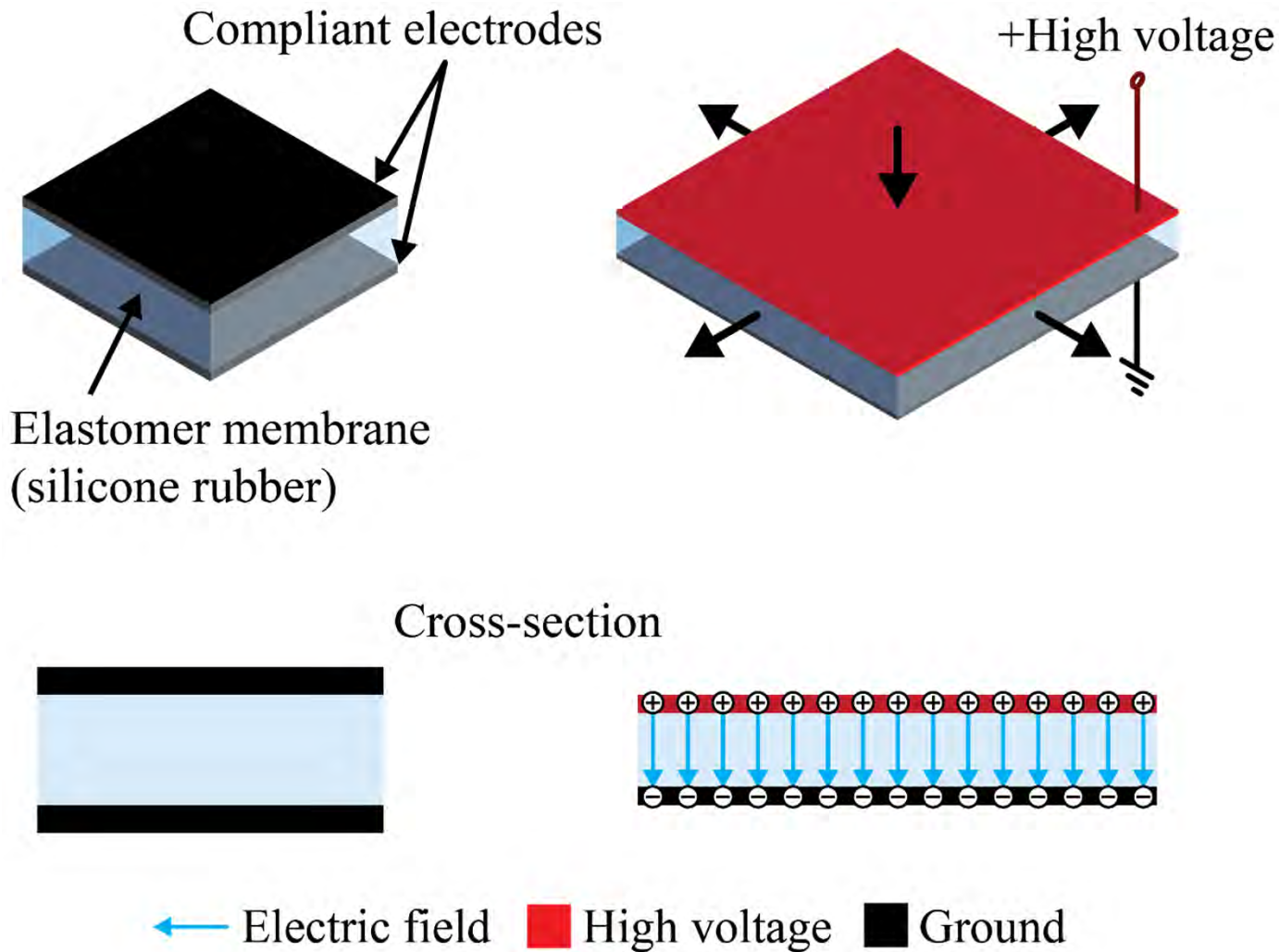


El-Atab, Nazek, et al. "Soft actuators for soft robotic applications: A review." *Advanced Intelligent Systems* 2.10 (2020): 2000128.

Detail a single soft actuator technology: Dielectric elastomer actuators (DEAs)

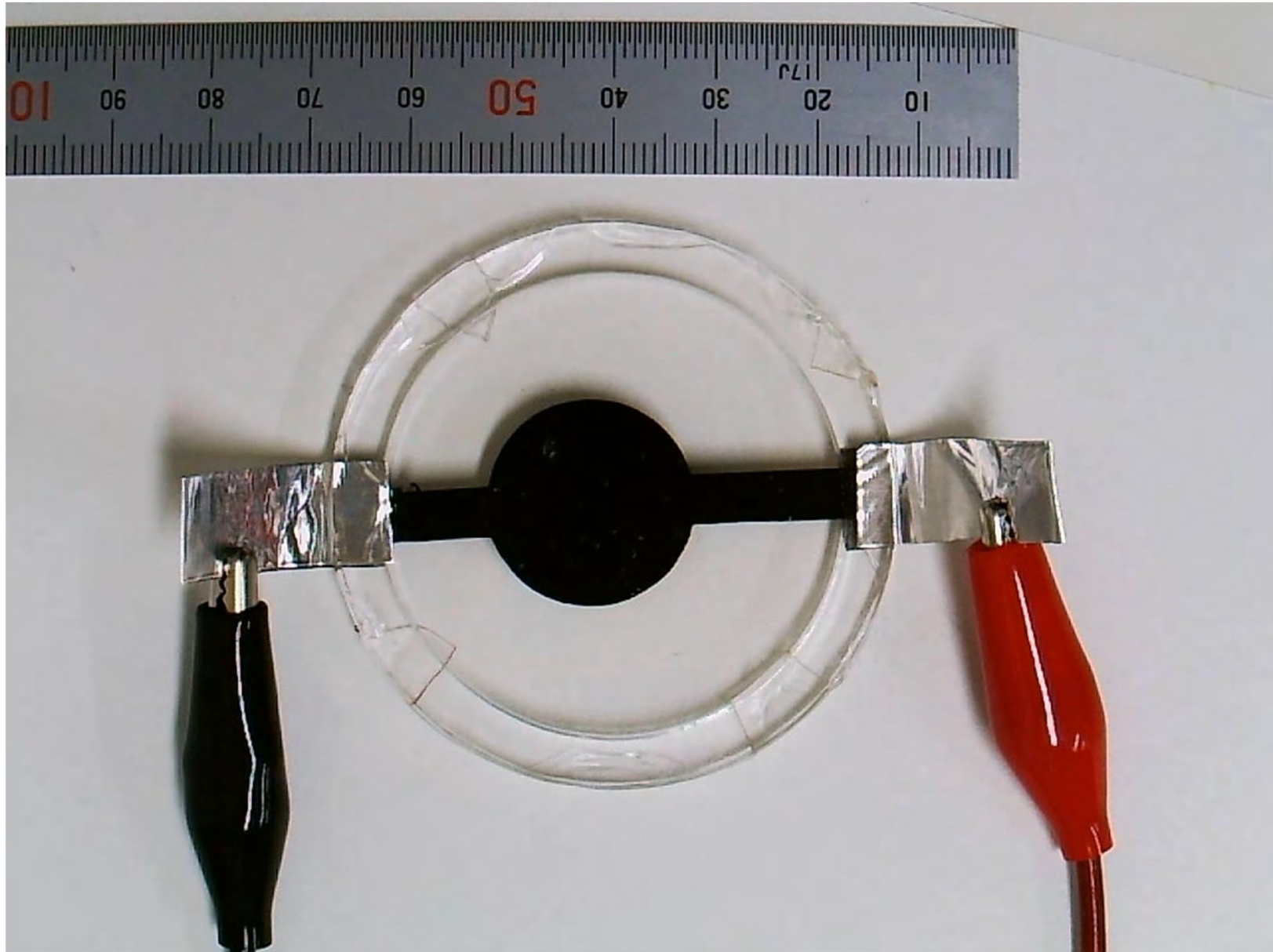
- **Actuator principle and configuration**
- Materials and fabrication methods
- Evaluation methods
- Soft robotic applications

Dielectric elastomer actuators (DEAs)



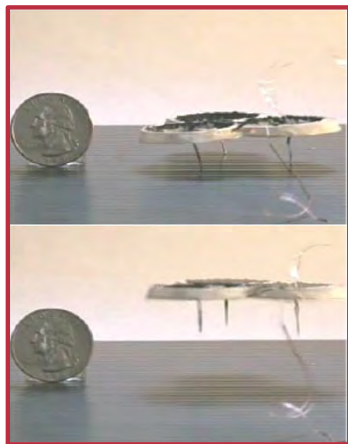
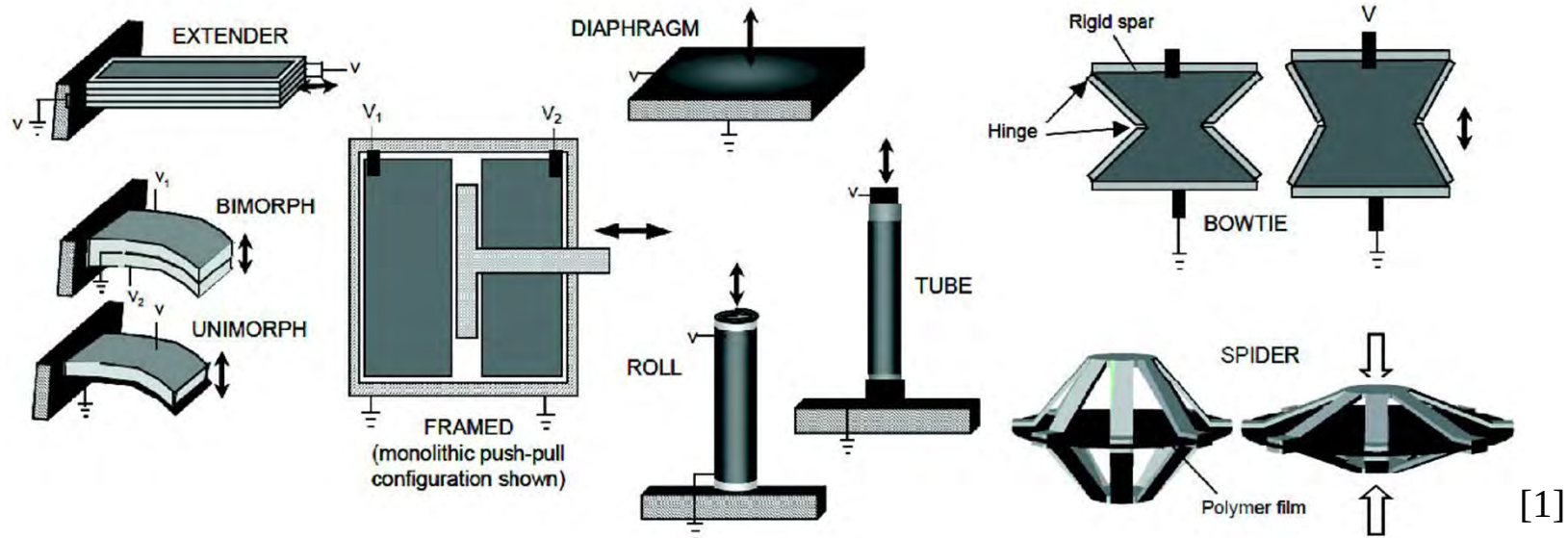
- **Simple**
- **Soft (elastic modulus is ~ 1 MPa)**
- **Fast (can be actuated at ~ 1 kHz)**
- **Large actuation strain (~ 100 % linear stroke)**
- **High voltage (a few kV)**
- **Self-sensing**

DEA in action



DEAs have been applied to many actuator configurations and robots

- [1] R. Kornbluh et al., in *Proc. SPIE*, San Diego, CA, USA, **2002**.
 [2] Q. Pei et al., in *Proc. SPIE*, San Diego, CA, USA, **2004**.
 [3] Q. Pei et al., *Smart Mater. Struct.* **2004**, *13*, N86.
 [4] C. Jordi et al., *Bioinspiration Biomim.* **2010**, *5*, 026007.



[2]



[3]



[4]

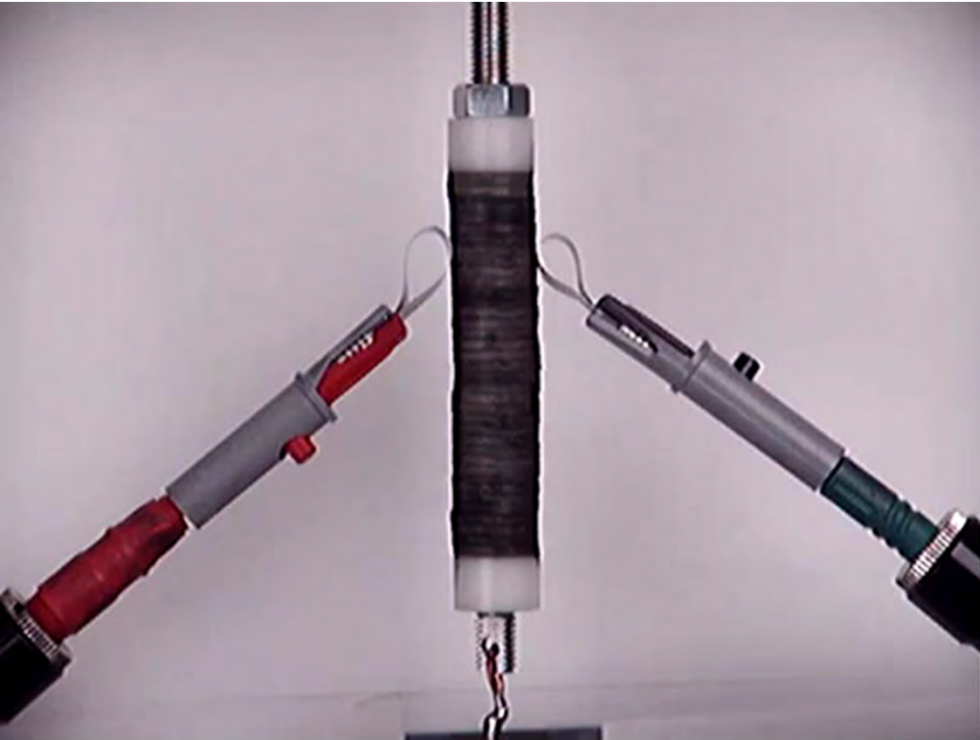
1cm

10 cm

1 m

Movies:

Stacked DEA and fish-like airship robot



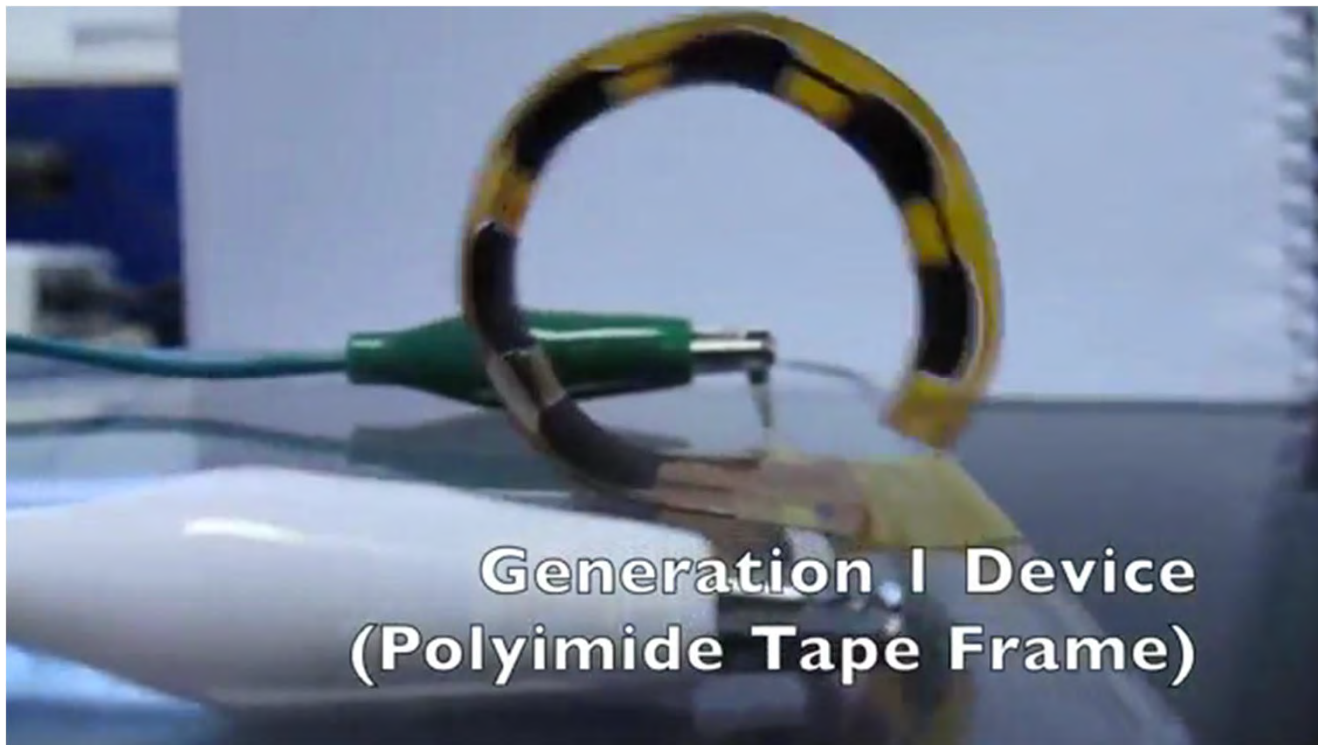
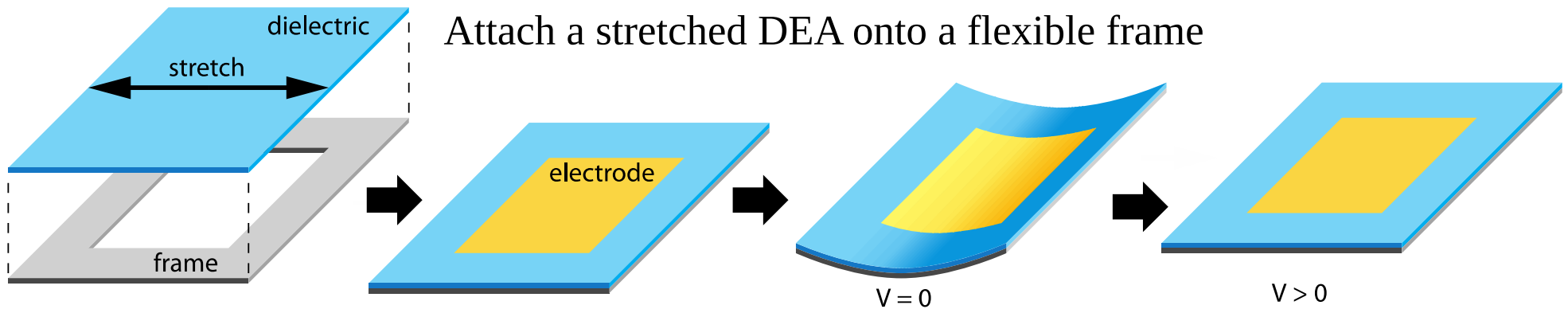
https://www.youtube.com/watch?v=Ga_IafGRWyE



https://www.youtube.com/watch?v=PCmUY1_qAoA

Jordi, Christa, Silvain Michel, and Erich Fink. "Fish-like propulsion of an airship with planar membrane dielectric elastomer actuators." *Bioinspiration & biomimetics* 5.2 (2010): 026007.

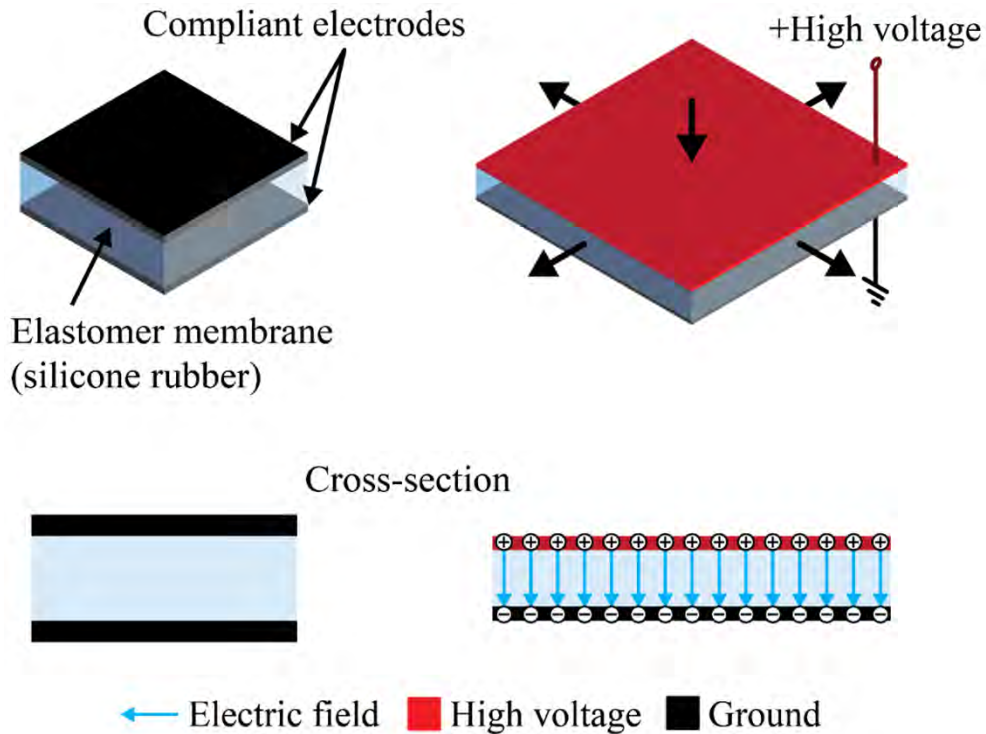
Movie: A DEA configuration to generate a large deformation



Application of voltage induces a bending deformation towards the flat state. This is a common configuration of DEA often employed in soft robots.

Araromi, Oluwaseun A., et al. "Rollable multisegment dielectric elastomer minimum energy structures for a deployable microsatellite gripper." *IEEE/ASME Transactions on mechatronics* 20.1 (2014): 438-446.

The actuation of DEAs results from electrostatic pressure (Maxwell stress)



Larger actuation performance can be obtained if:

- Relative permittivity is high
- Voltage is high
- Thickness of membrane is small
- Dielectric strength is high
- Young's modulus is low

Assuming the volume of membrane is constant (i.e., incompressible)

$$(s_X + 1)(s_Y + 1)(s_Z + 1) = 1$$

Strain in the thickness direction $s_Z = \frac{p}{Y}$

Young's modulus of membrane

Electrostatic pressure* $p = \epsilon_0 \epsilon_r E^2 = \epsilon_0 \epsilon_r \left(\frac{V}{d} \right)^2$

Permittivity of vacuum ϵ_0
 Relative permittivity of membrane ϵ_r
 Electric field E
 Voltage V
 Thickness of membrane d

*F. Carpi et al., *Dielectric elastomers as electromechanical transducers* 2011, Elsevier.

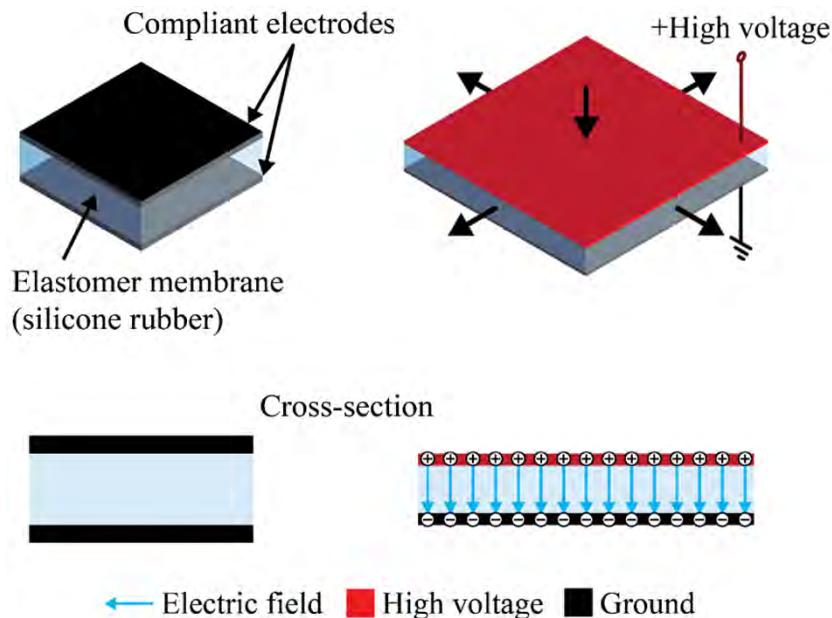
Representative ways to improve the actuation performance of DEAs

Higher performance comes from

- High relative permittivity
- High dielectric strength
- Small Young's modulus

Method

- Mix fillers into the membrane mat.
- Polymer network modification
- Stretch the membrane prior to the actuation (pre-stretch)



However, there are trade-offs. For instance, even if the relative permittivity increases, the dielectric strength decreases.

Detail a single soft actuator technology: Dielectric elastomer actuators (DEAs)

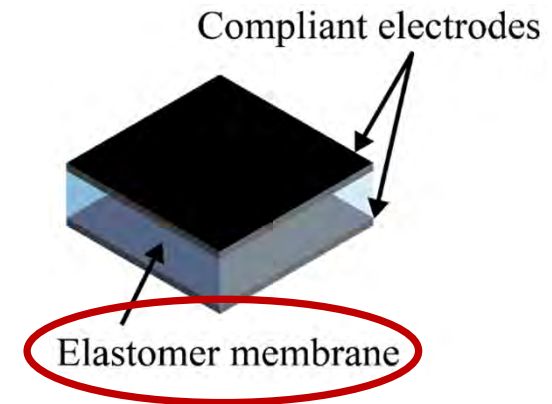
- Actuator principle and configuration
- **Materials and fabrication methods**
- Evaluation methods
- Soft robotic applications

Material of DEA membrane

Acrylic and silicone type materials are the two mainstreams.

Acrylic type : Large output but slow (due to viscoelasticity)

Silicone type : Small output but fast

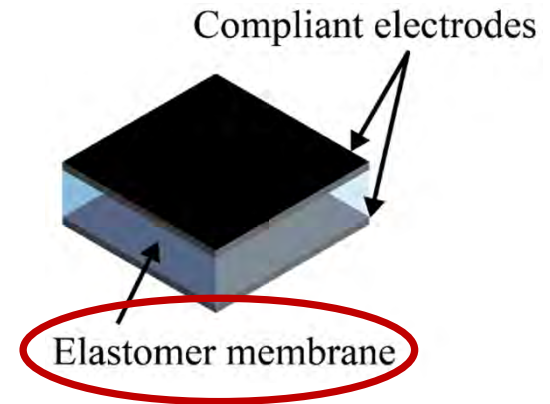


Parameter	Acrylic type	Silicone type
Maximum actuation strain (%)	380	120
Maximum stress (MPa)	8.2	3.0
Frequency response (Hz)	~10	>1,000
Maximum electric field (MV/m)	440	350
Relative permittivity	4.5-4.8	2.5-3.0
Durability (number of actuation cycles)	>10 ⁶	>10 ⁶

Membrane materials

Heat and light (UV) curable materials are widely used.

Representative products:



Silicone type

Sylgard 184 (Dow Corning)



Silicone type

Ecoflex (Smooth-On)



Silicone type

Elastosil Film 2030 (Wacker)



Acrylic type

VHB4905 (3M)

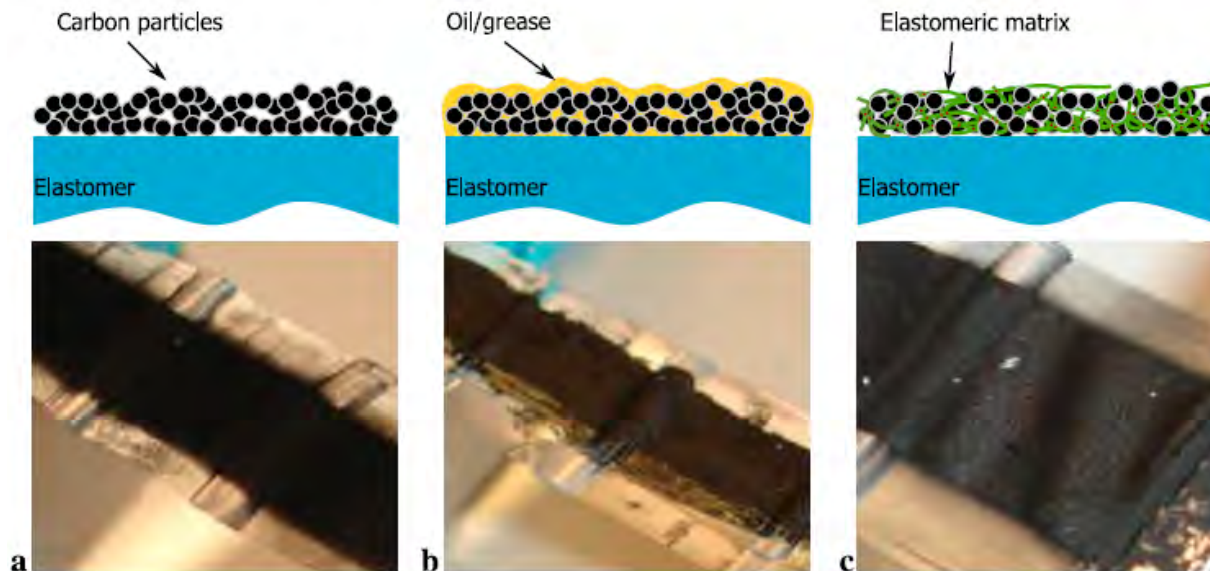
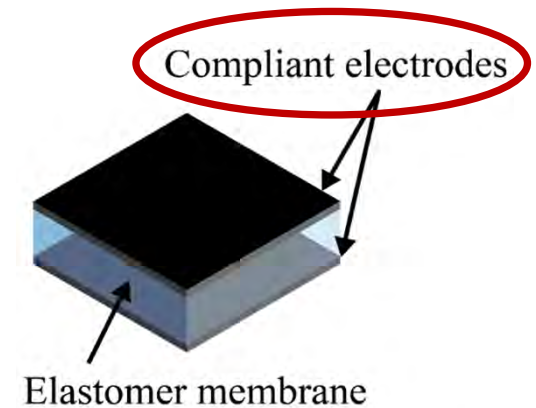
- Those provided in liquid form (Sylgard and Ecoflex)
Shape forming is required according to the desired shape (curing time: 1~2 hours)
- Those provided in film form (Elastosil and VHB)
Convenient for use as it is, but film thickness is fixed

Electrode materials

Characteristics required for electrode materials

Soft, thin, high conductivity, easy to prepare and pattern, safe

- Nanoparticles (left)
Carbon black, carbon nanotubes, graphene, silver nanowires, silver, gold, titanium, etc.
- Liquid metal, ionized gel, grease (center)
Gallium-indium alloy, NaCl-containing gel
- Conductive membrane (mixing conductive particles) (right)



- Direct patterning of nanoparticles or grease is easy, but the electrodes can come off and contaminate the surroundings. A bit unsafe.
- Conductive elastomers need careful preparation, but are stable with high adhesion. Actuation is slightly smaller.

Rosset, Samuel, and Herbert R. Shea. "Flexible and stretchable electrodes for dielectric elastomer actuators." *Applied Physics A* 110.2 (2013): 281-307.

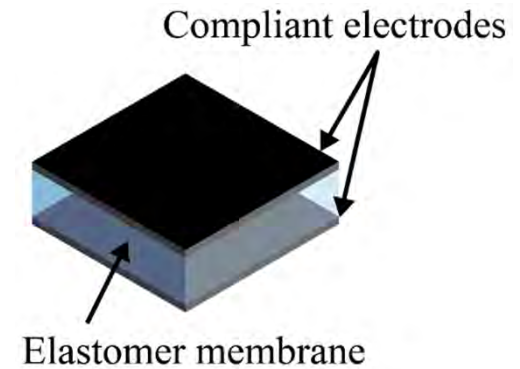
Method to fabricate membranes and pattern electrodes

Membrane

- Blade casting
- Spin coating
- Pad printing
- Ink jet (incl. 3D printing)

Electrode

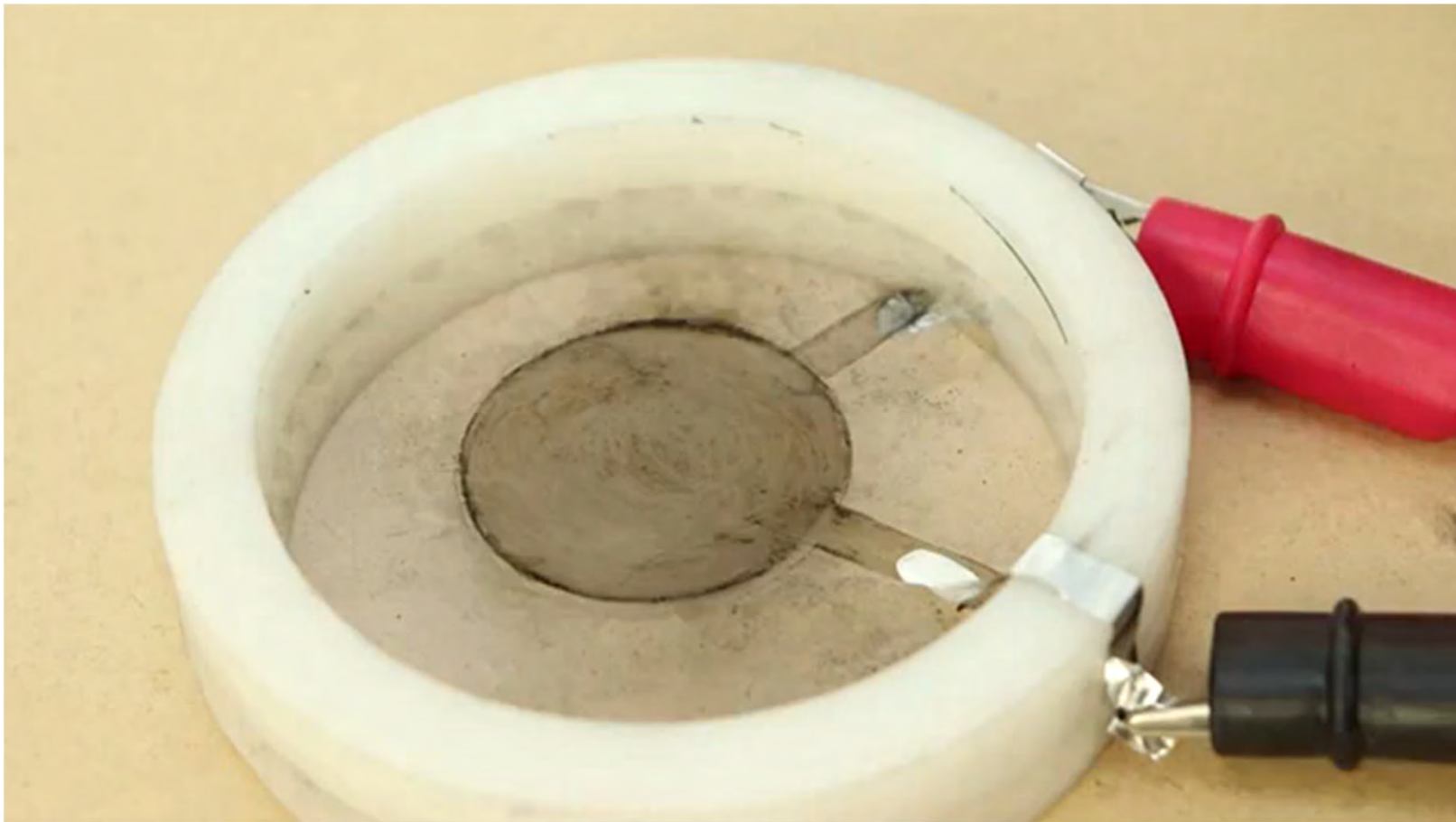
- Blade casting
- Spin coating
- Pad printing
- Ink jet (incl. 3D printing)
- Spray coating
- Hand painting



Hand painting

Easiest method: hand-paint electrodes on commercial membranes

Example of fabrication using acrylic membrane (VHB4910, 3M) and carbon black



Open Soft Machines
<http://opensoftmachines.com/2018/04/dea/?lang=ja>

Blade casting

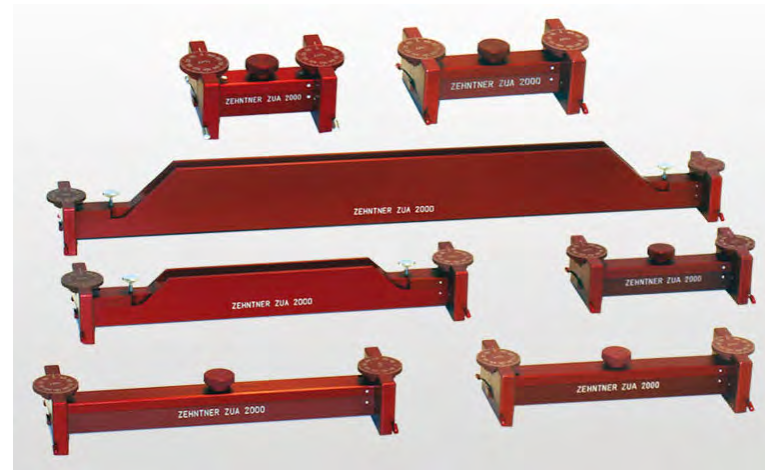
Rosset, Samuel, et al. "Fabrication process of silicone-based dielectric elastomer actuators." *JoVE (Journal of Visualized Experiments)* 108 (2016): e53423.
<https://www.jove.com/video/53423/fabrication-process-of-silicone-based-dielectric-elastomer-actuators>

Film applicator



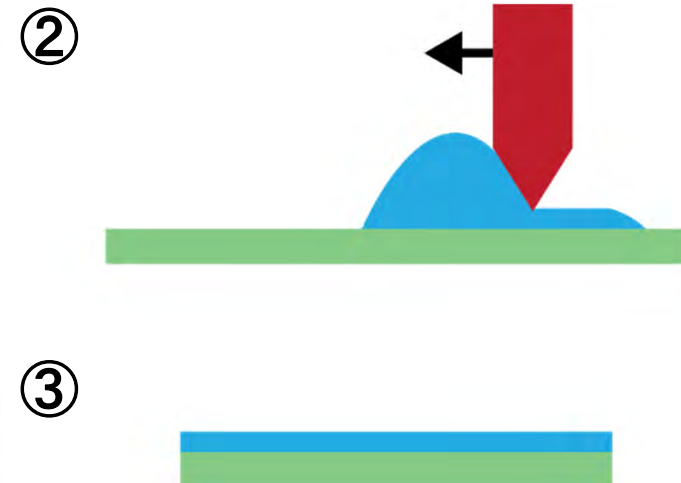
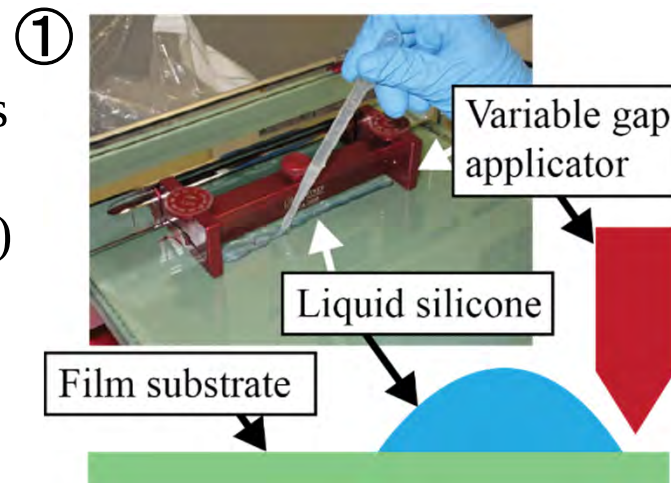
Zehntner, ZAA2300

Gap applicator



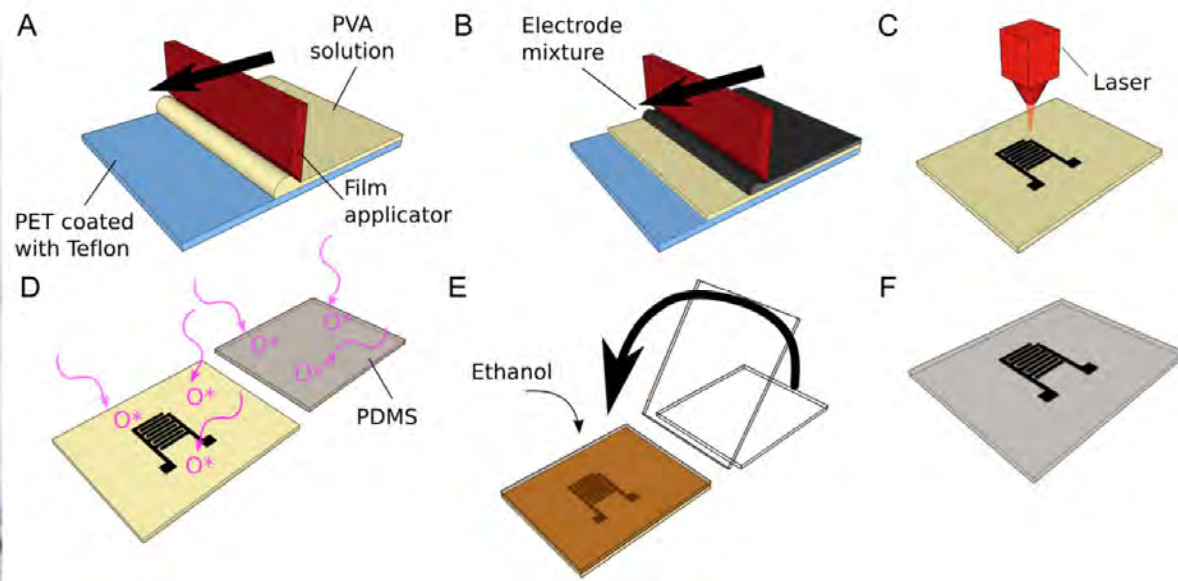
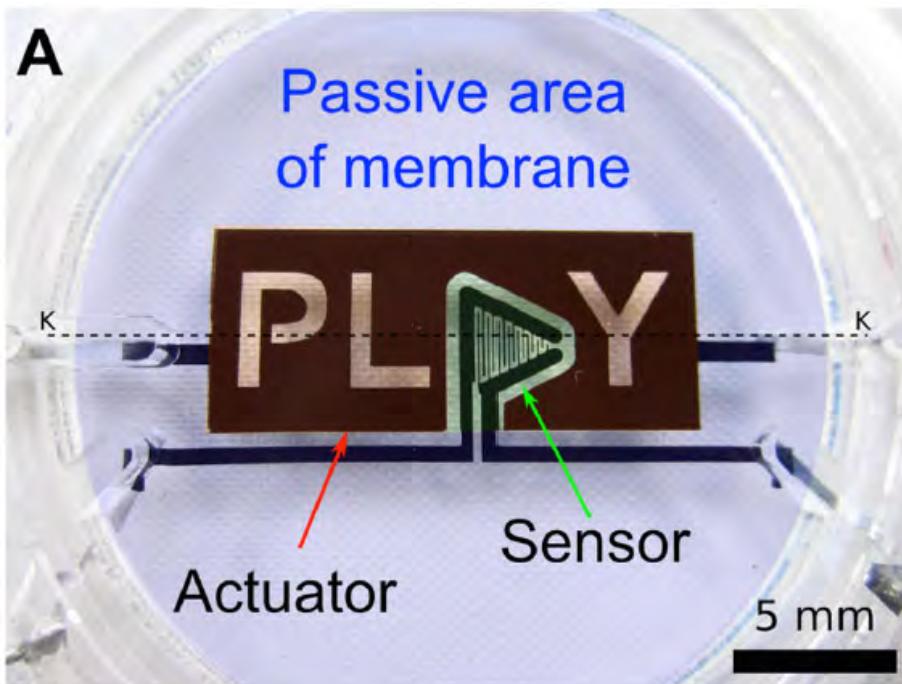
Zehntner, ZUA2000

- Desired membrane thickness can be obtained.
- Large area ($\sim 20 \text{ cm} \times 30 \text{ cm}$)
- Conductive membrane can also be fabricated.



Blade casting

Example of a device fabricated by blade casting:



Membrane and electrode layer made by blade casting are bonded by oxygen plasma. The electrode is engraved with a CO₂ laser.

*Araromi, Oluwaseun A., Samuel Rosset, and Herbert R. Shea. "High-resolution, large-area fabrication of compliant electrodes via laser ablation for robust, stretchable dielectric elastomer actuators and sensors." *ACS applied materials & interfaces* 7.32 (2015): 18046-18053.

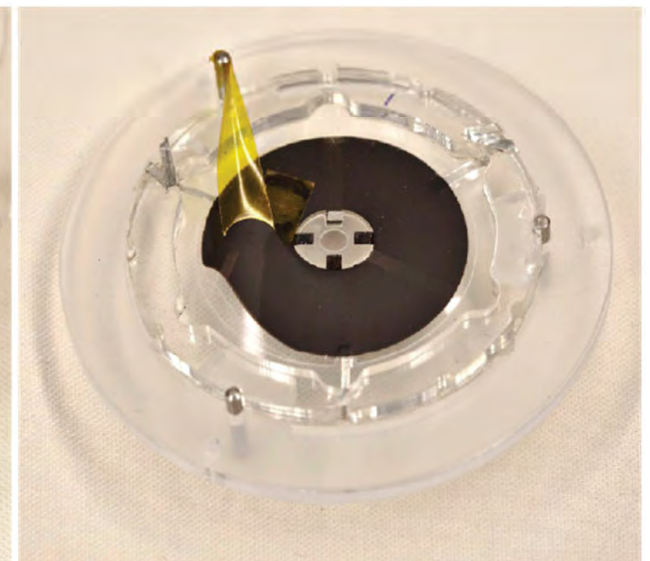
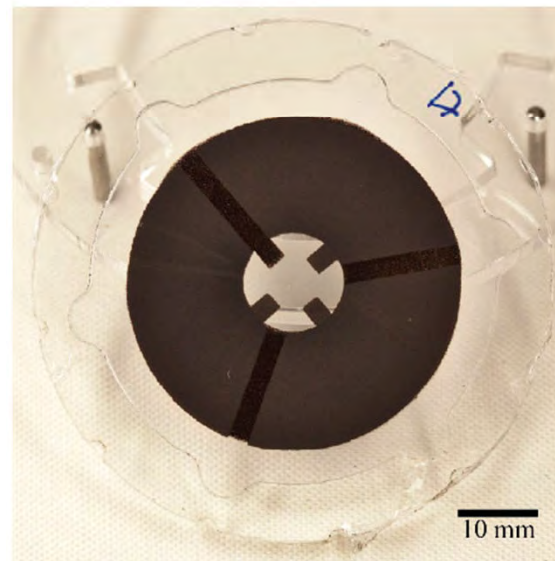
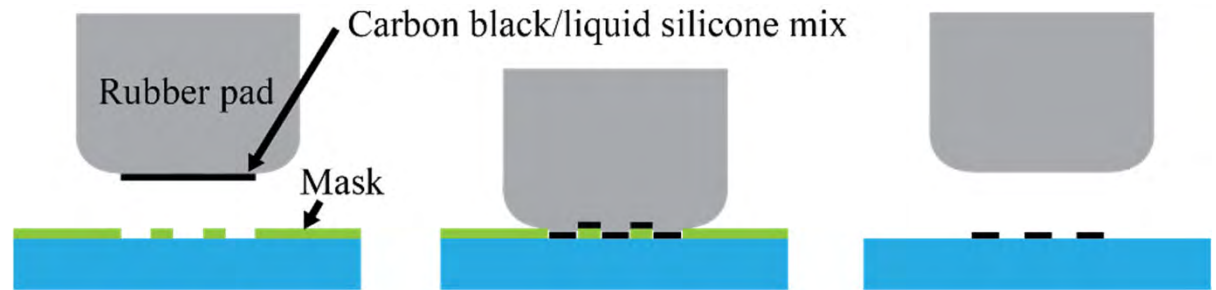
Pad printing

Rosset, Samuel, et al. "Fabrication process of silicone-based dielectric elastomer actuators." *JoVE (Journal of Visualized Experiments)* 108 (2016): e53423.
<https://www.jove.com/video/53423/fabrication-process-of-silicone-based-dielectric-elastomer-actuators>

Pad printer



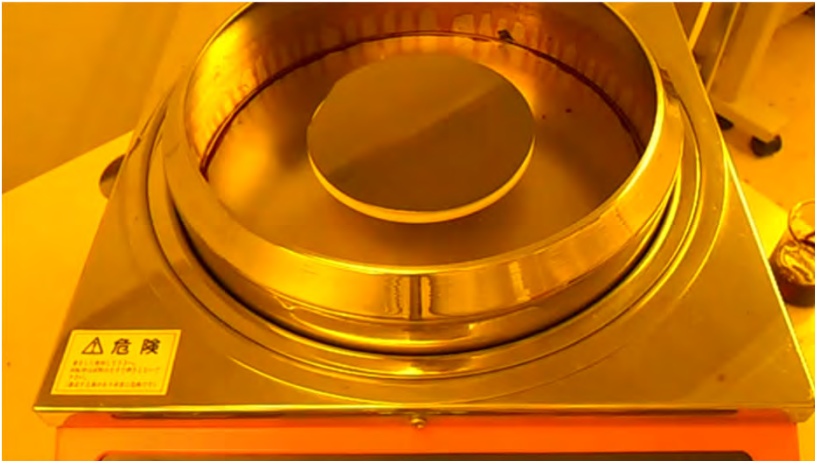
Teca-Print, TPM101



- Thin electrodes can be easily formed (thickness 1-5 μm)
- Electrode area is about $\Phi 100$ mm
- Non conductive membrane can also be produced, but with lower precision in thickness

Spin coating

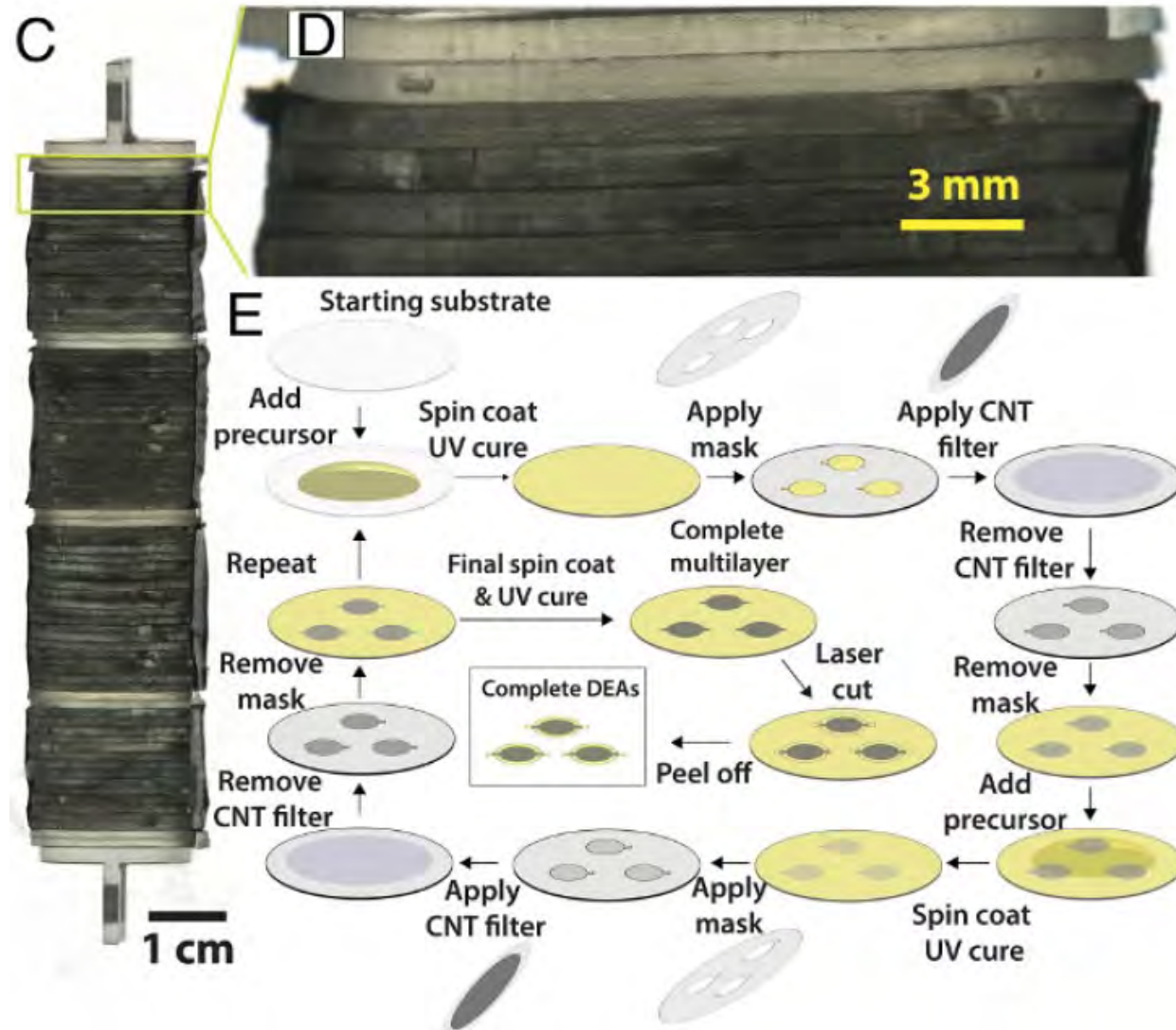
Spin coater



<https://www.youtube.com/watch?v=ScGi0O3YTA0>

- Desired membrane thickness can be obtained
- High accuracy of membrane thickness
- Conductive membranes can also be produced
- Relatively small area

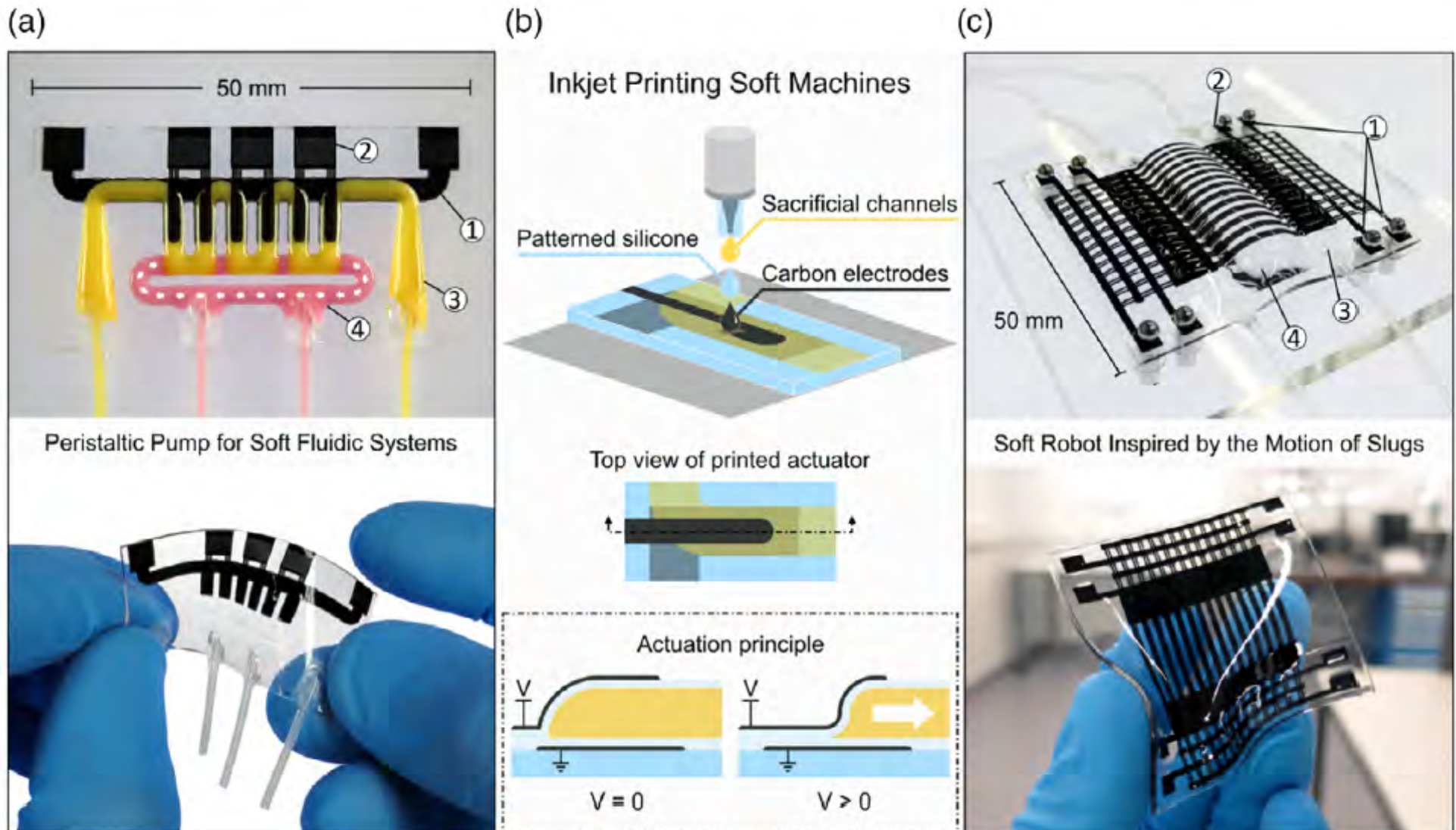
Example of a stacked DEA



Ink jet (incl. 3D printing)

Schlatter, Samuel, et al. "Inkjet Printing of Complex Soft Machines with Densely Integrated Electrostatic Actuators." *Advanced Intelligent Systems*: 2000136.

- Can be produced DEAs in various shapes with high precision, but the preparation of inks is often difficult and the equipment is complex.

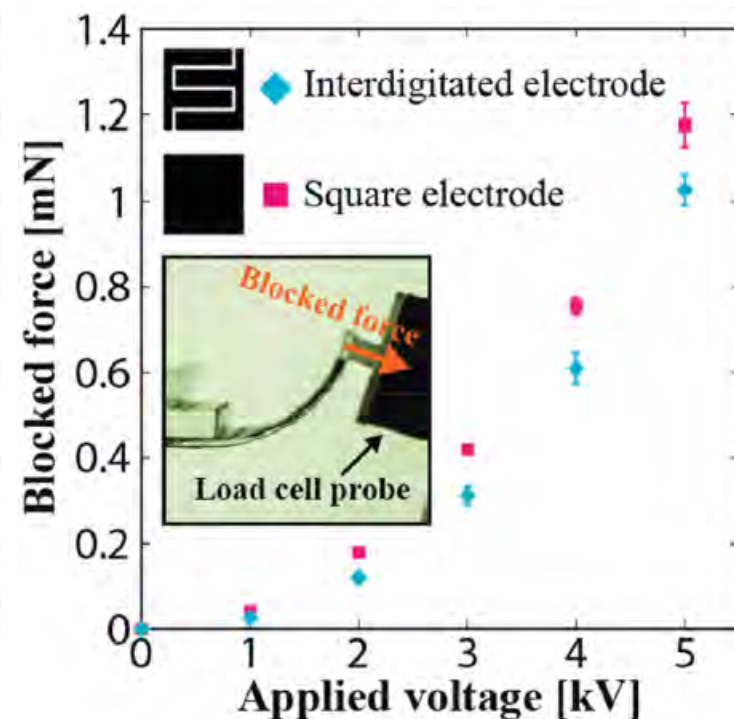
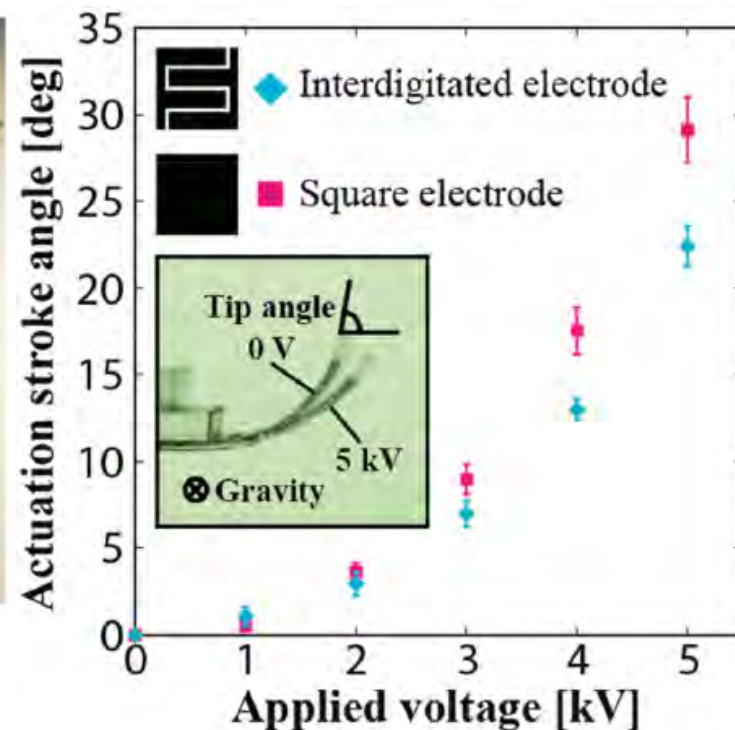
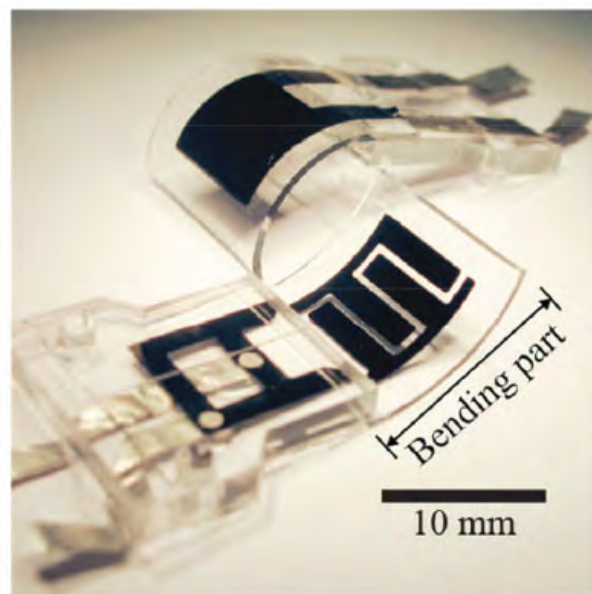


Detail a single soft actuator technology: Dielectric elastomer actuators (DEAs)

- Actuator principle and configuration
- Materials and fabrication methods
- **Evaluation methods**
- Soft robotic applications

Metrics to evaluate actuation performance of DEAs

In many cases, displacement and force are measured



Displacement (angle, strain): measured by camera or laser displacement sensor
Force: measured by a load cell

Equipment to drive DEAs; High-voltage power supplies

- DC/DC converter (Direct use)



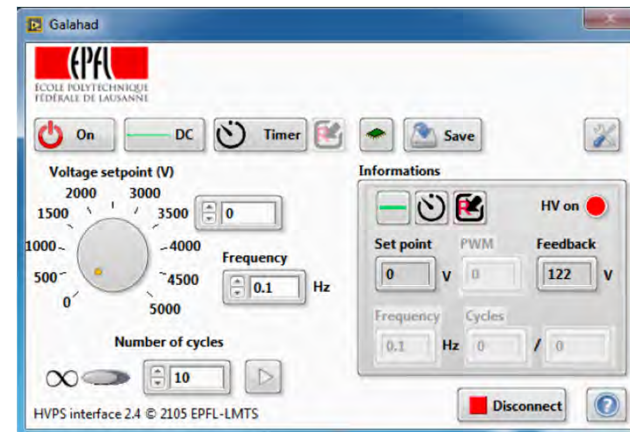
Example: XP Power CB101N (10 kV)

- Commercially available high-voltage power supply

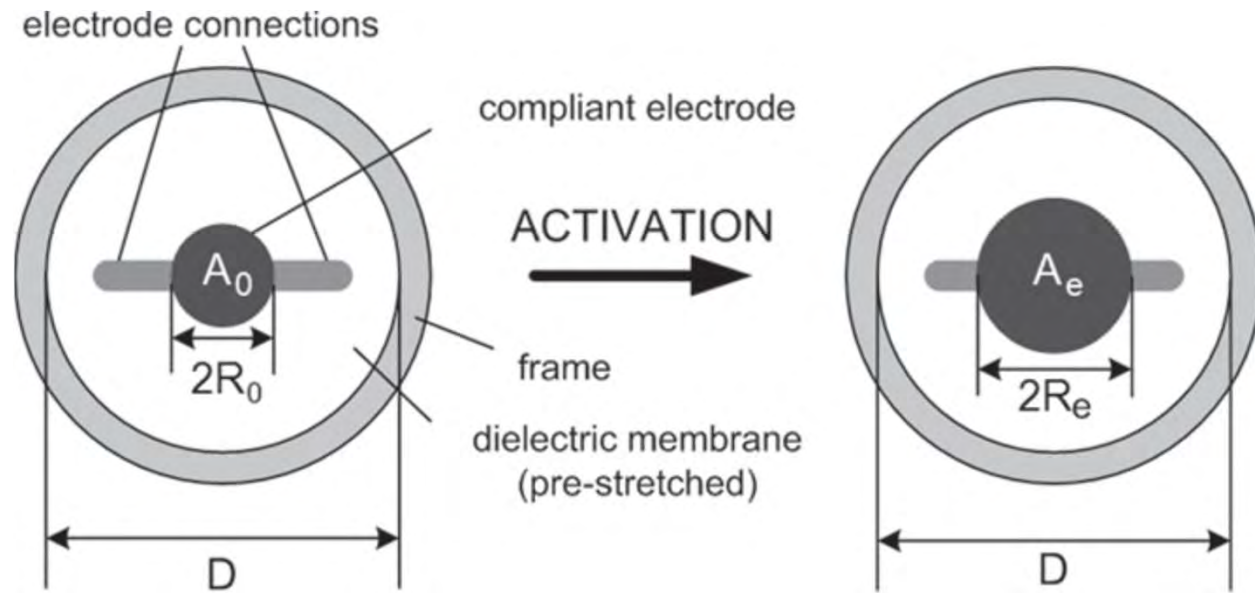
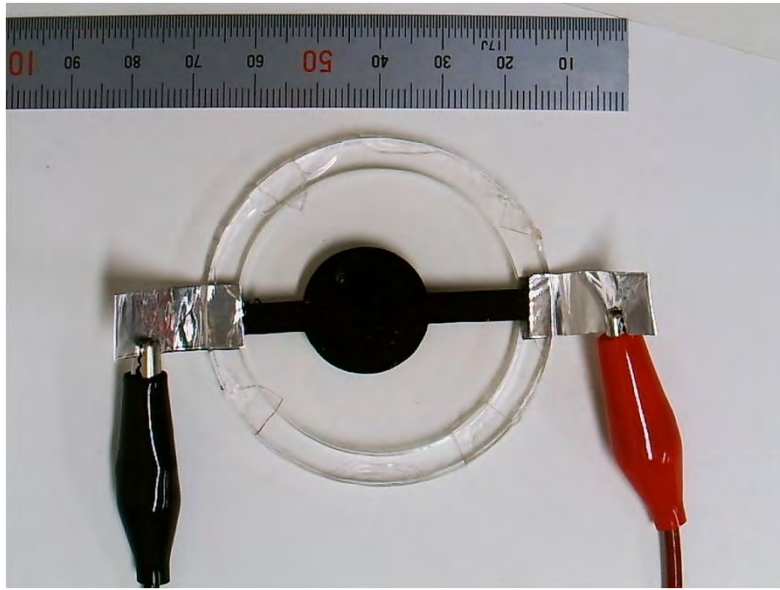


Example: Matsusada HEOP-5B6 (5 kV)

- Open source high voltage power supply (5 kV)



Standard evaluation sample: Circular DEAs



Carpi, Federico, et al. "Standards for dielectric elastomer transducers." *Smart Materials and Structures* 24.10 (2015): 105025.

- Useful for testing new membranes and electrode materials
- Frequency response can also be visualized
- Membrane diameter D should be 3~10 times the electrode diameter $2R_0$
- Membrane should be pre-stretched

Strain in the thickness direction

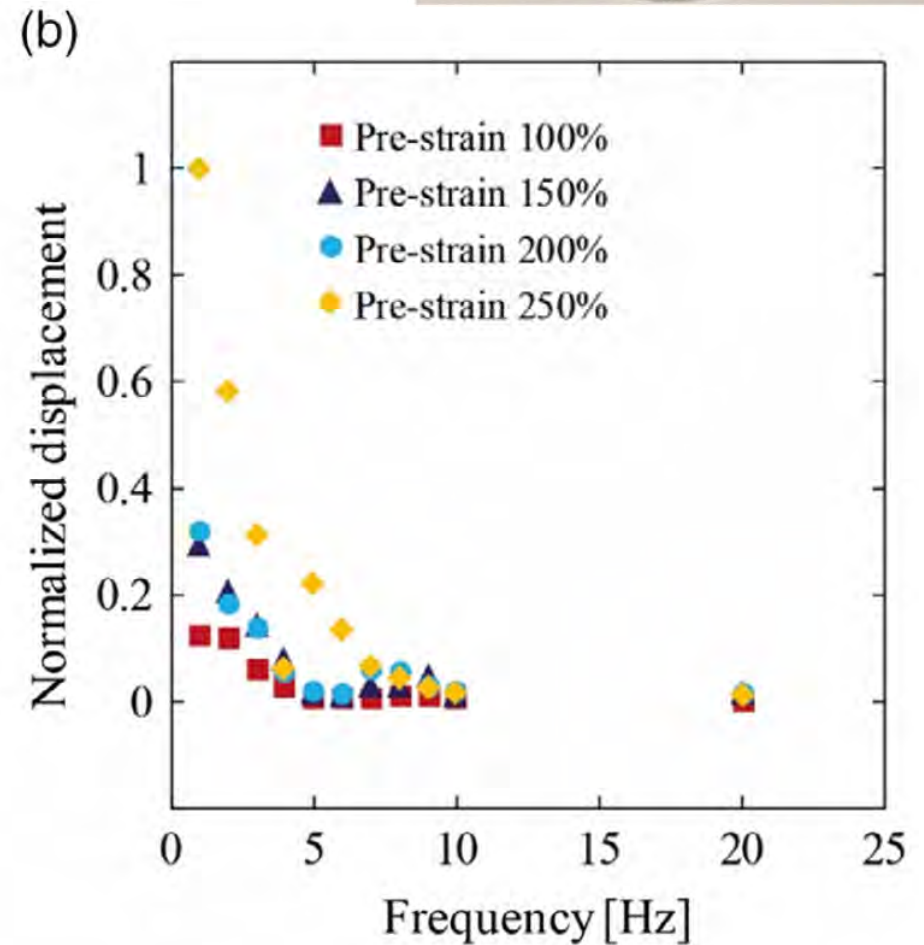
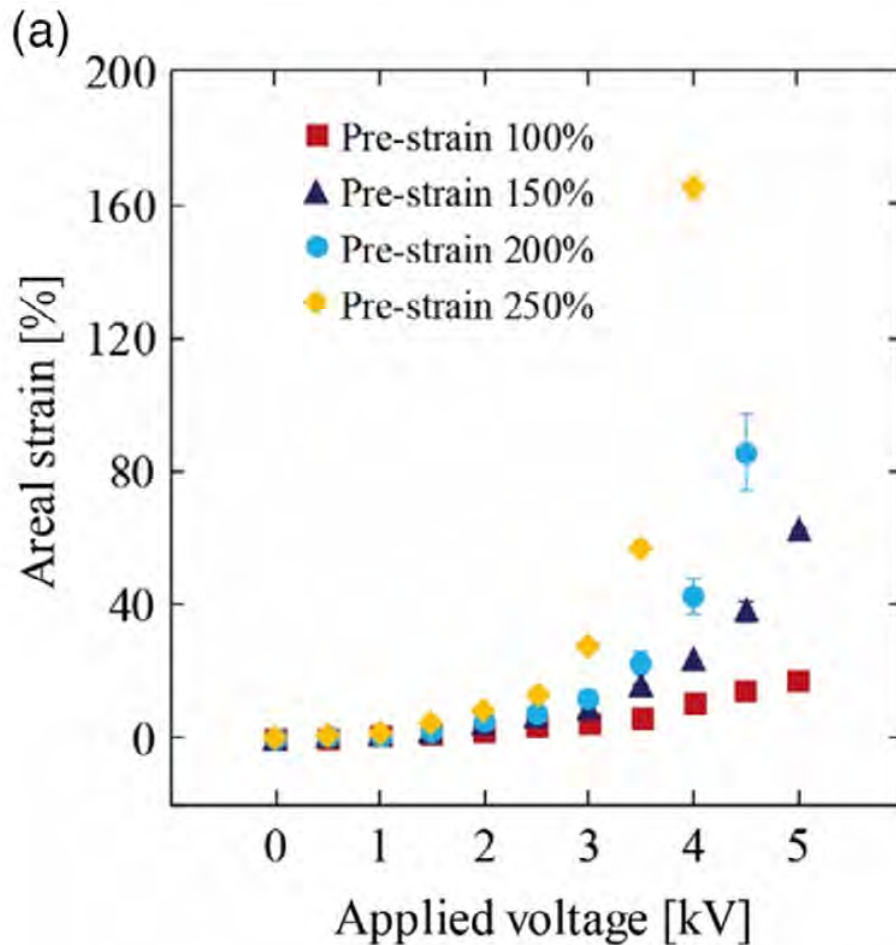
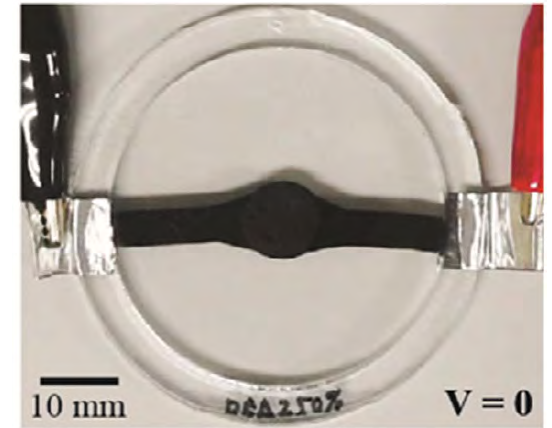
$$S_{e,z} = \frac{1}{(S_{e,r} + 1)^2} - 1$$

Strain in the radial direction

$$S_{e,r} = \frac{R_e}{R_0} - 1$$

Standard evaluation sample: Circular DEAs

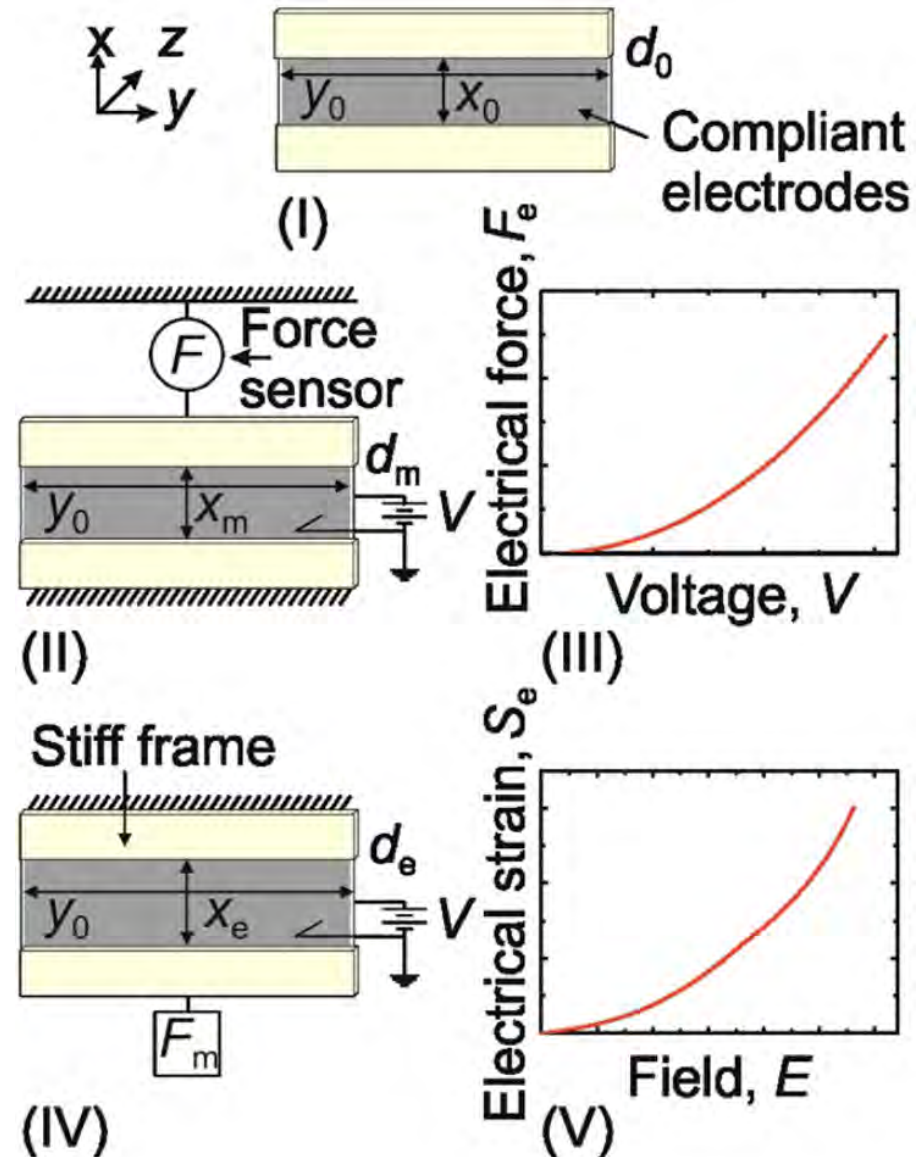
Example of measured result



Kanno, Ryo, Toshiaki Nagai, and Jun Shintake. "Rapid Fabrication Method for Soft Devices Using Off-the-Shelf Conductive and Dielectric Acrylic Elastomers." *Advanced Intelligent Systems*: 2000173.

Standard evaluation sample: Pure-shear DEAs

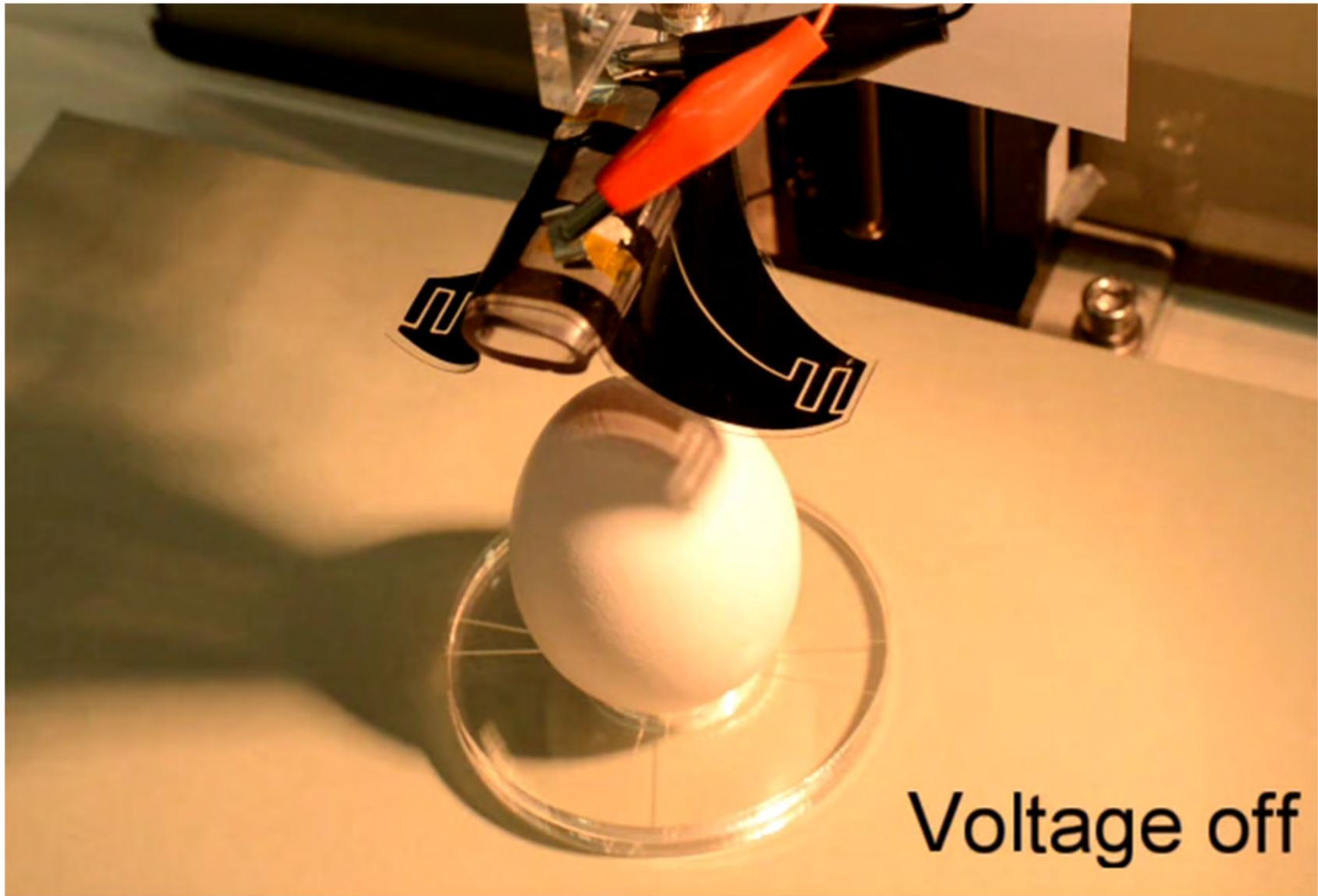
- Only vertical (x) actuation occurs by constraining horizontal (y) displacement
- Actuator aspect ratio should be 1:5~1:10
- (II) Fixing the displacement yields the actuation stress (force)
- (IV) Actuation strain with respect to the input is obtained by fixing the load



Detail a single soft actuator technology: Dielectric elastomer actuators (DEAs)

- Actuator principle and configuration
- Materials and fabrication methods
- Evaluation methods
- **Soft robotic applications**

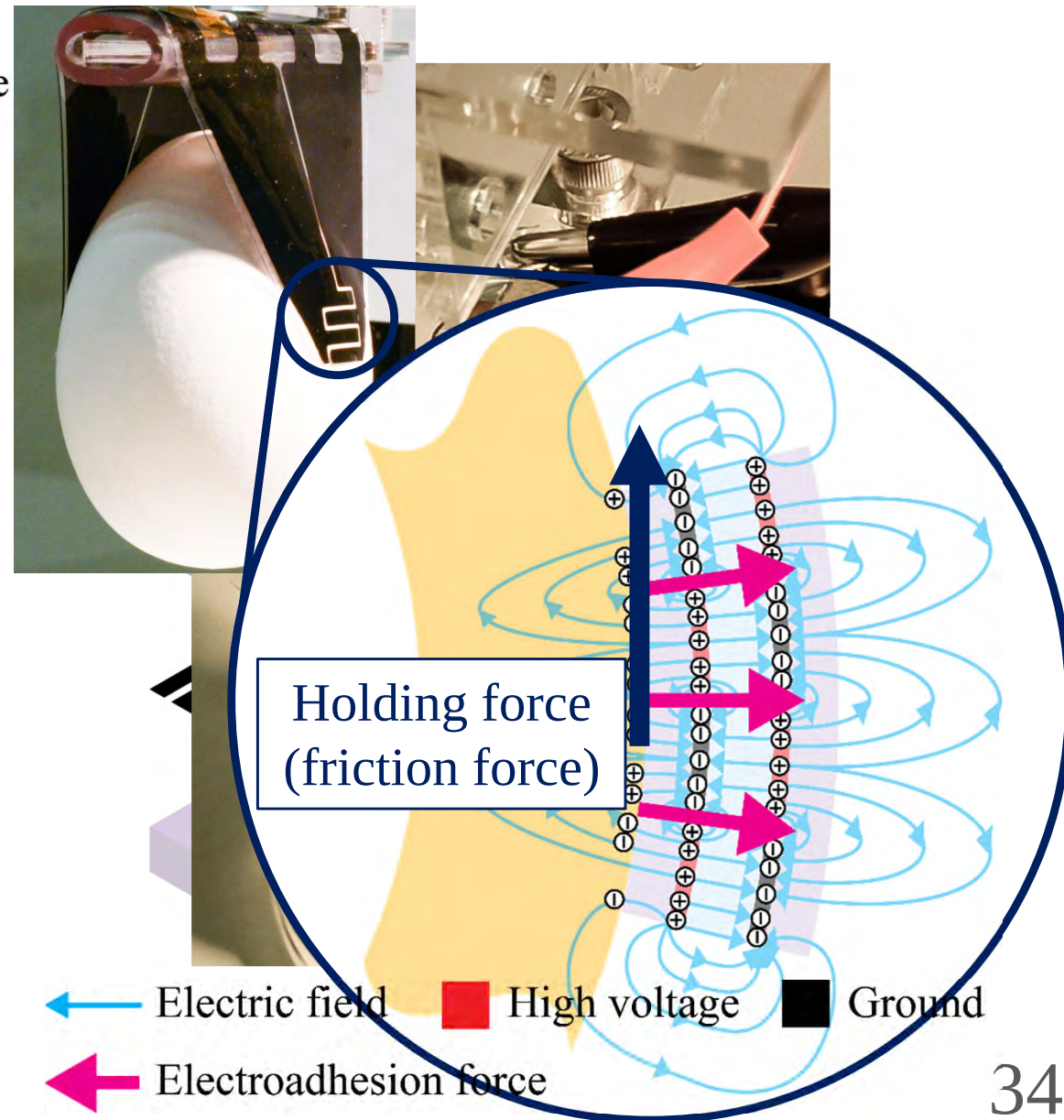
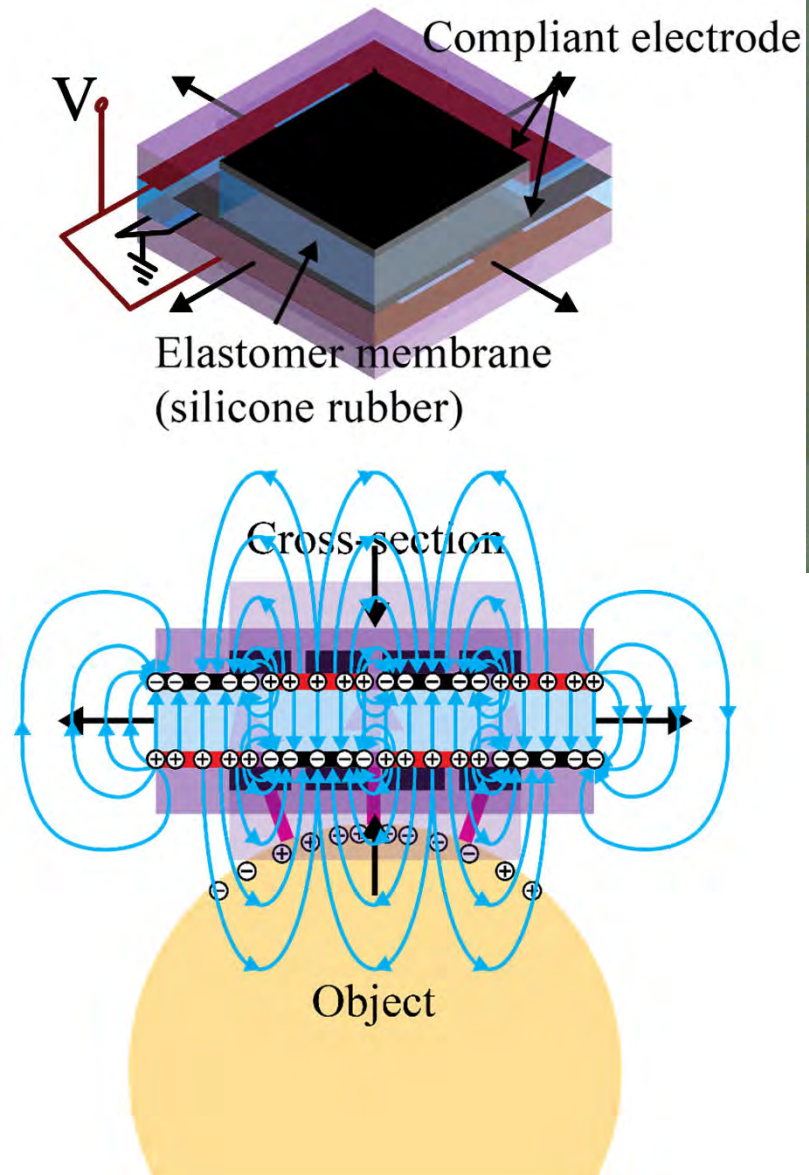
Soft gripper



Raw egg (weight 60.9 grams)

×1

Gripper holds objects by electro-adhesion



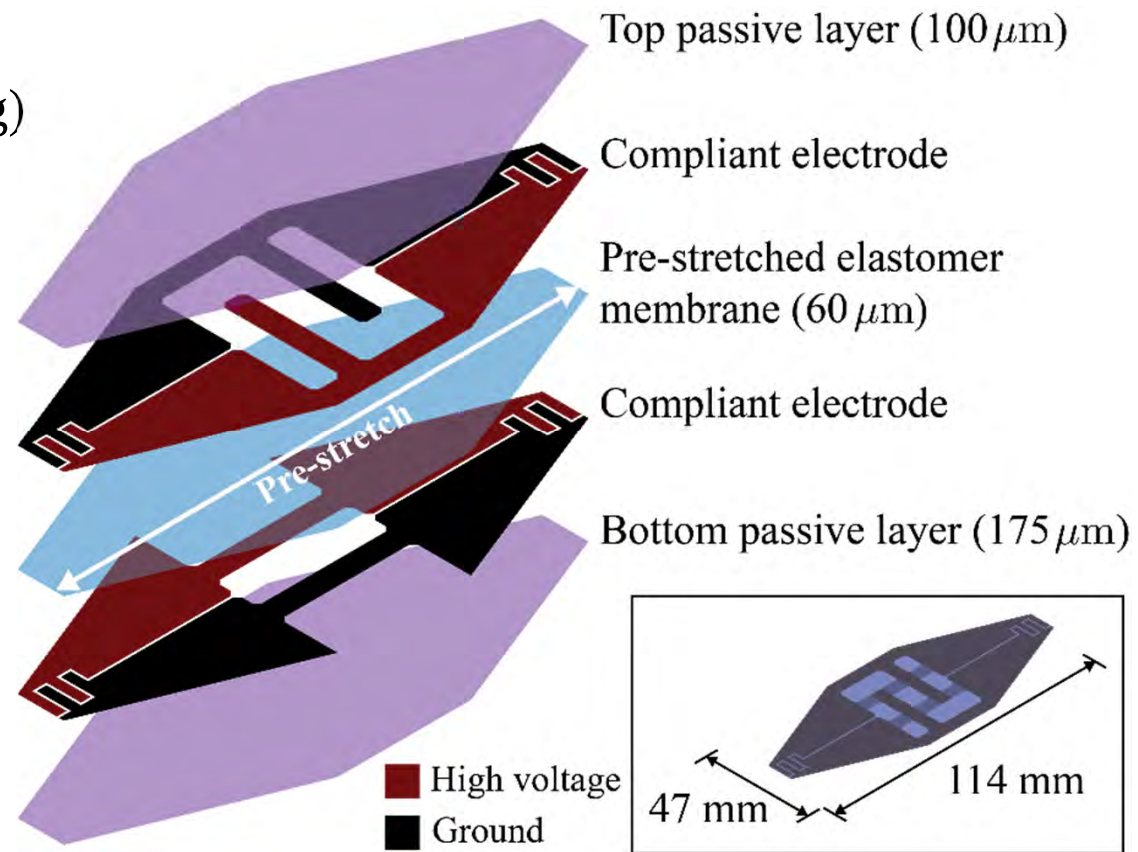
Materials and fabrication method used for the gripper

Materials

- Structure: Sylgard 184 (Dow Corning)
- Membrane: CF19-2186 (NuSil)
- Electrodes: Ketjenblack EC-300J
Silbione LSR 4305
Solvent (iso-octane)

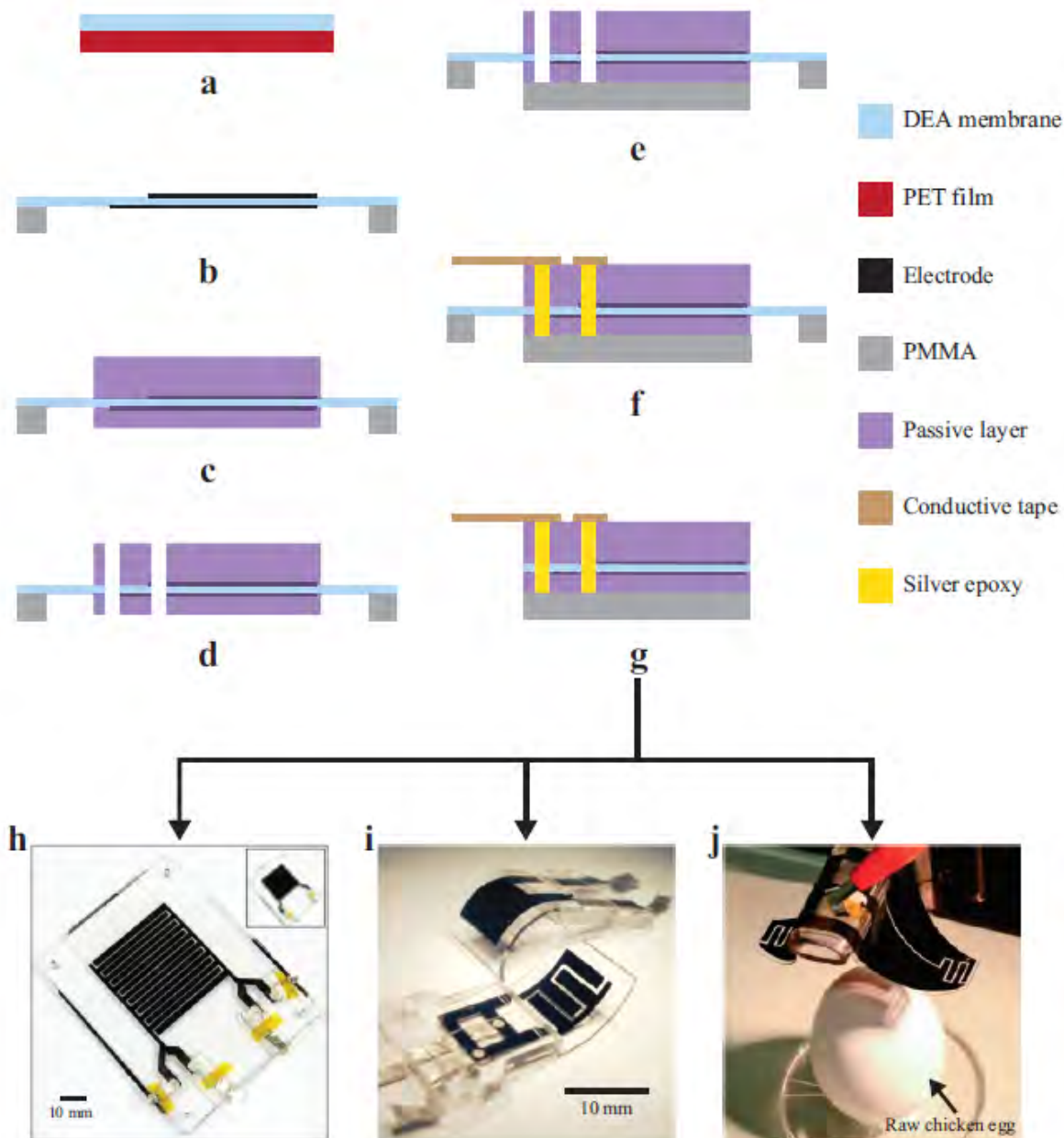
Fabrication method

- Structure: Blade casting
- Electrodes: Pad printing
- Bonding of each part: O₂ plasma



Structural composition of the gripper

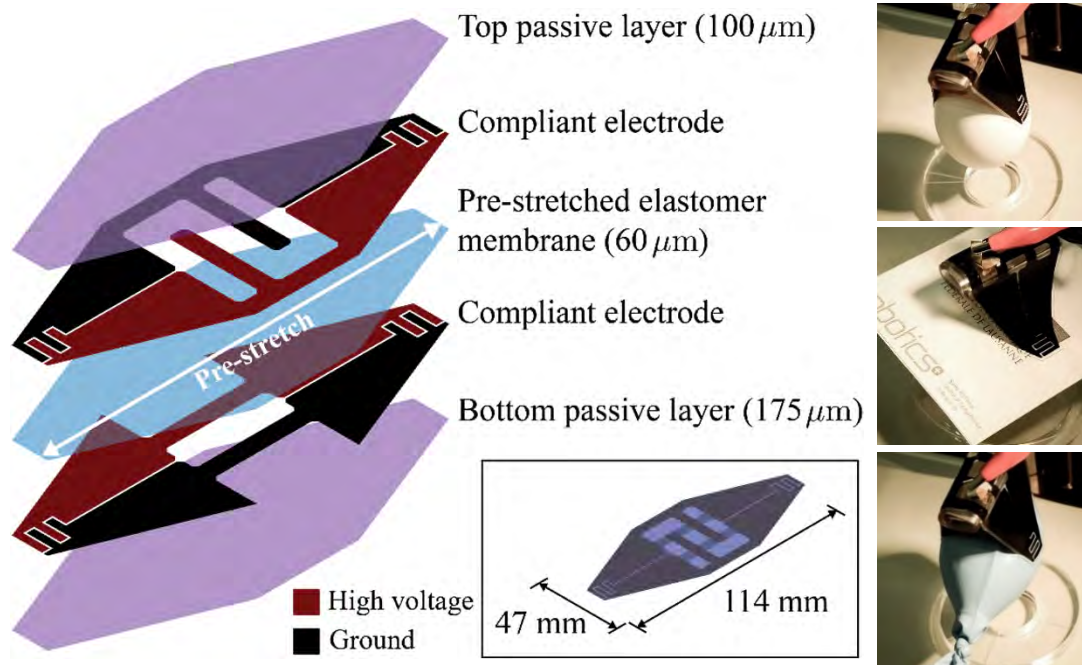
Fabrication process used for the gripper



- CF19-2184 is blade-cast on PET film and cured in an oven at 80 °C (60 μm)
- Cured CF19-2184 is pre-stretched and held, and electrodes are applied by pad printing (3 μm). Electrodes are cured in an oven (80 °C)
- Sylgard 184 membranes (100, 75 μm) are made by blade casting and bonded by O₂ plasma
- Make holes in the electrodes to establish connections
- Place the sample on an acrylic sheet
- Fill the hole with silver epoxy
- Apply conductive tape to enable voltage application to the device

The soft gripper has various features

- Capable of grasping objects of various shapes
- High flexibility in shape design
- Lightweight (up to 1.5 g)
- Capable of holding more than 1000 times its own weight
- Applications in the manufacturing and food industry
- Vegetable and fruit gathering
- Application to other robots such as drones

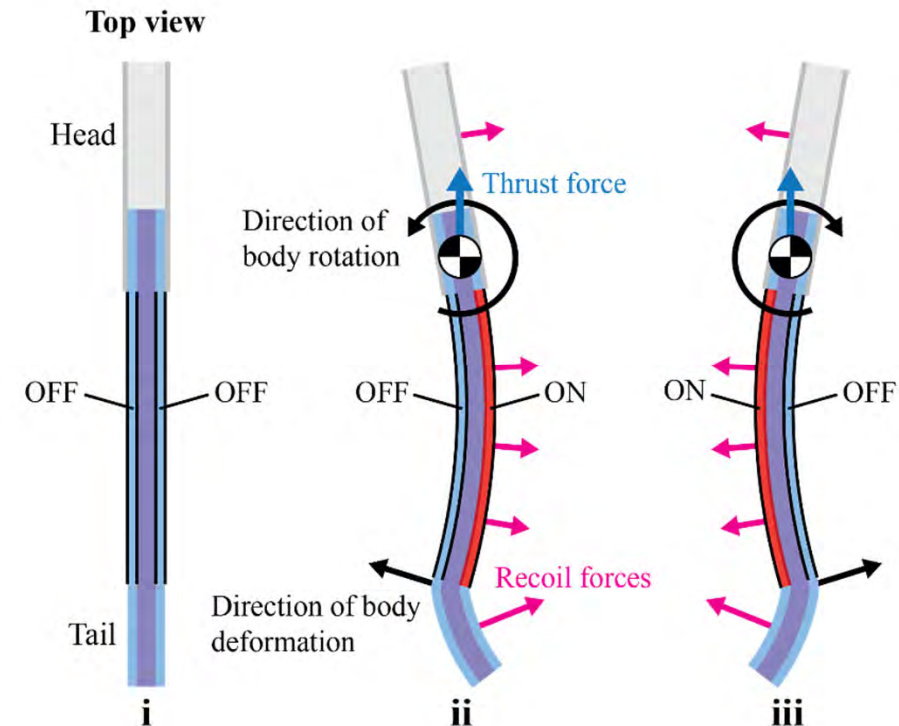
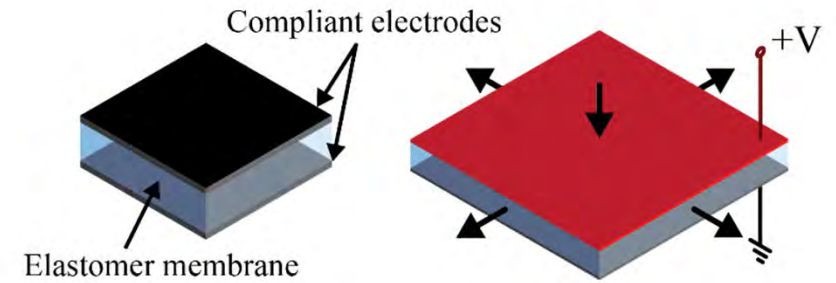
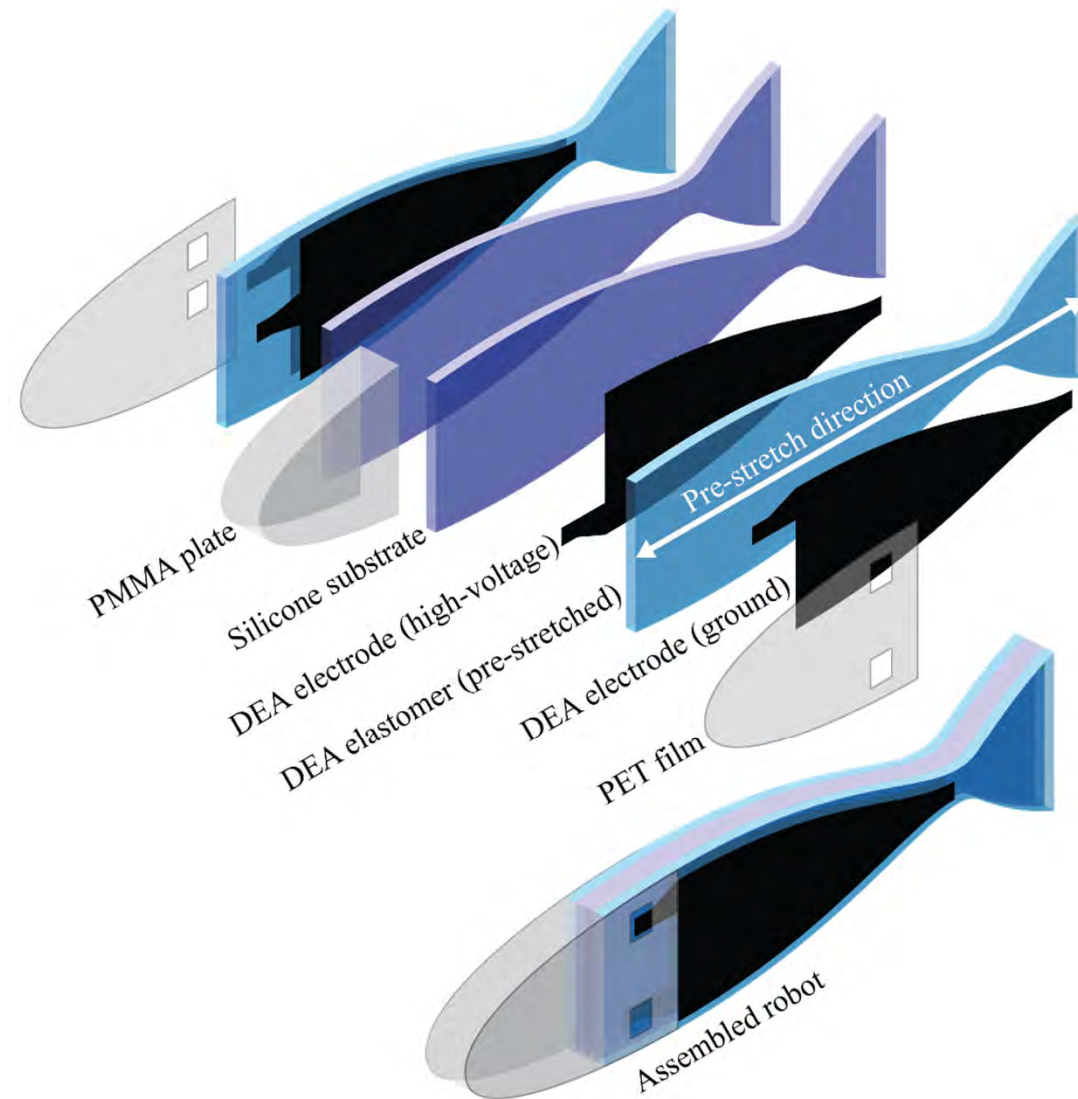


Structural composition of the gripper



Biomimetic underwater robot

DEAs can be used underwater when insulation measures are taken.

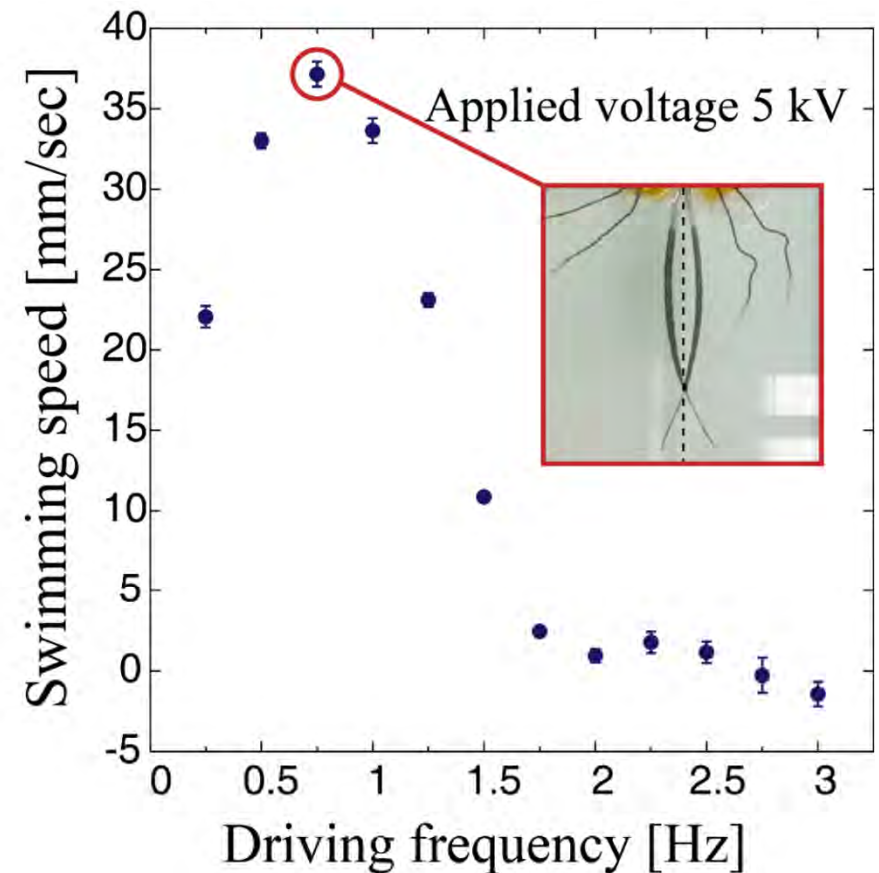
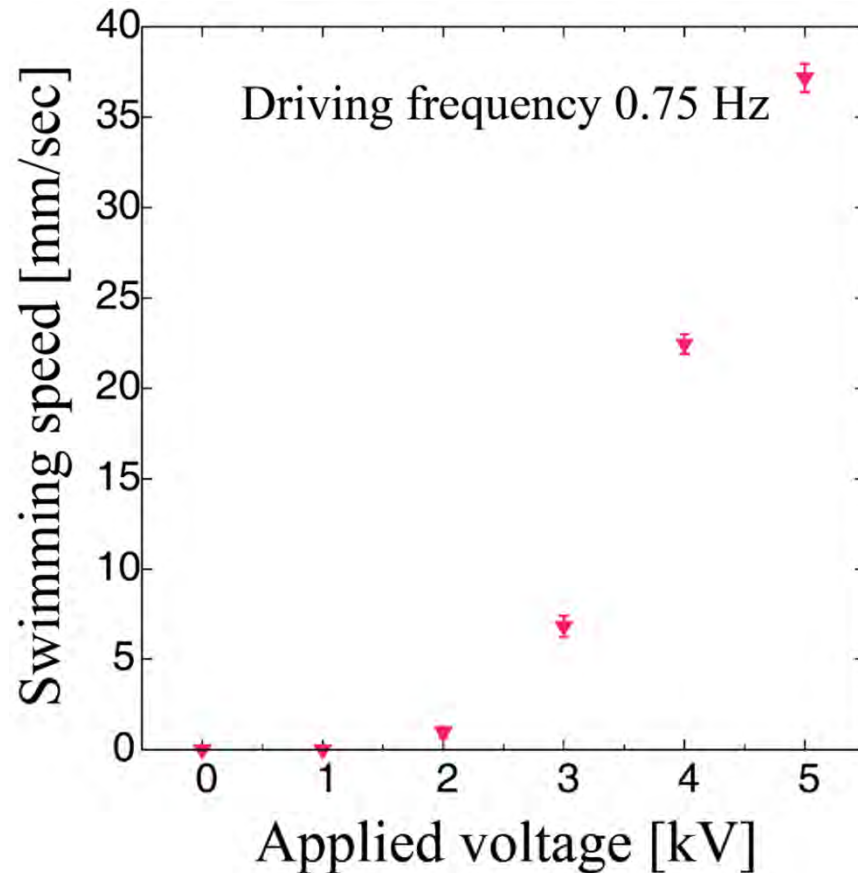


Swimming of DEA fish robot

Driving frequency: 0.25 Hz

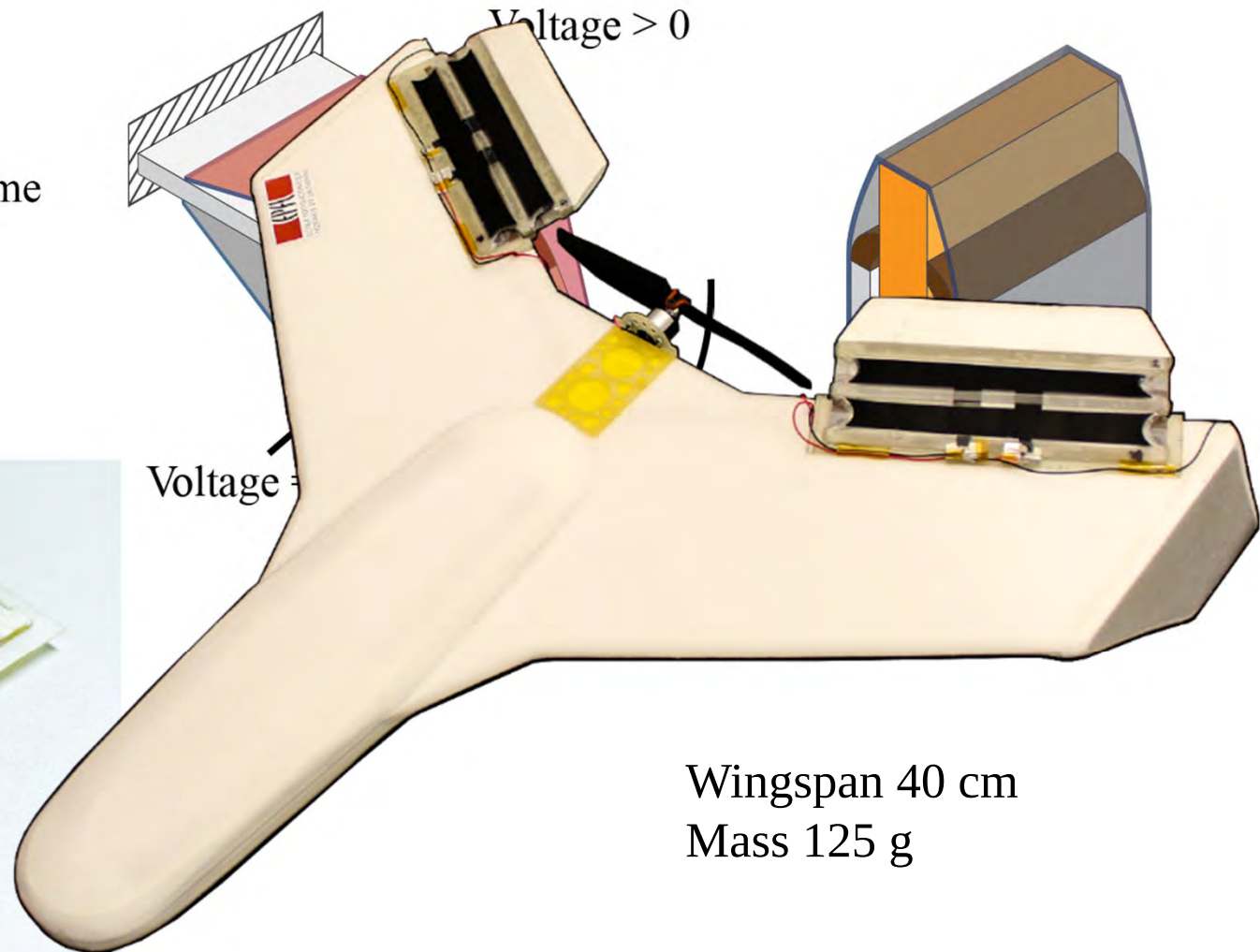
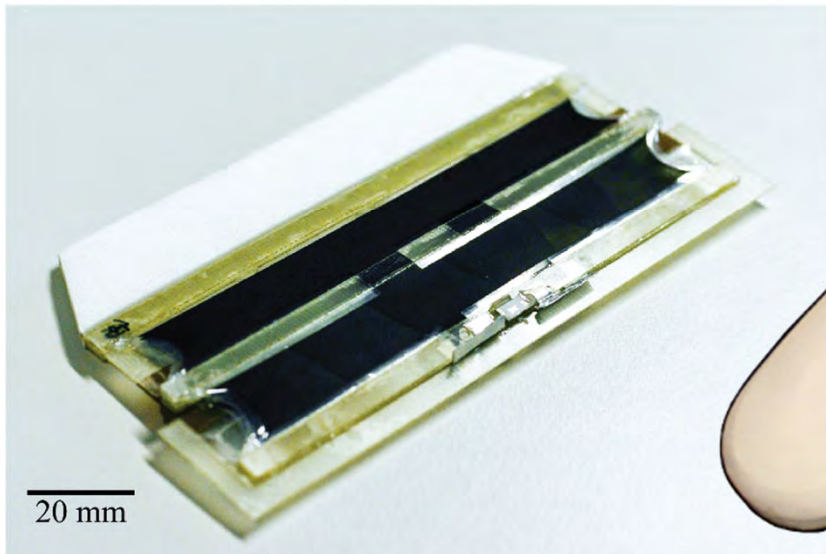
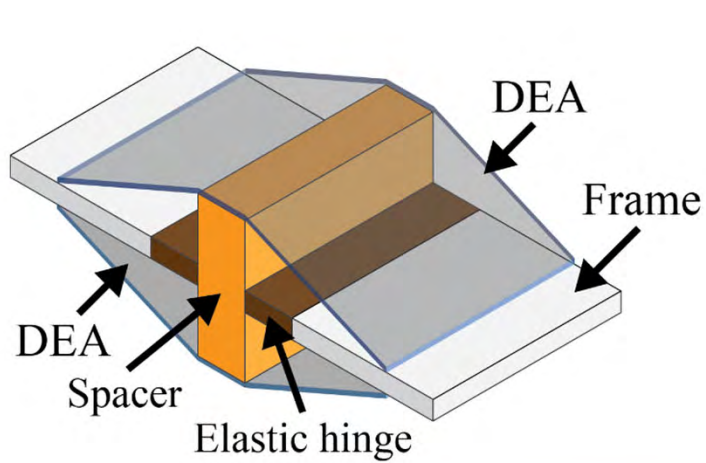
Applied voltage: 5 kV

The swimming speed of the robot can be controlled by the applied voltage and frequency

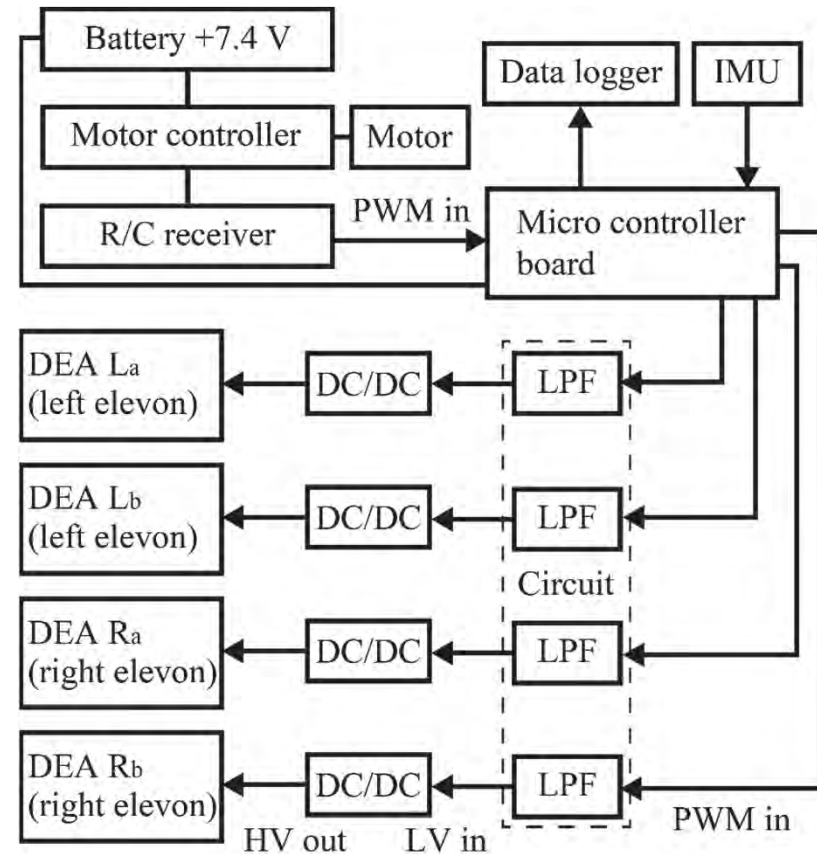
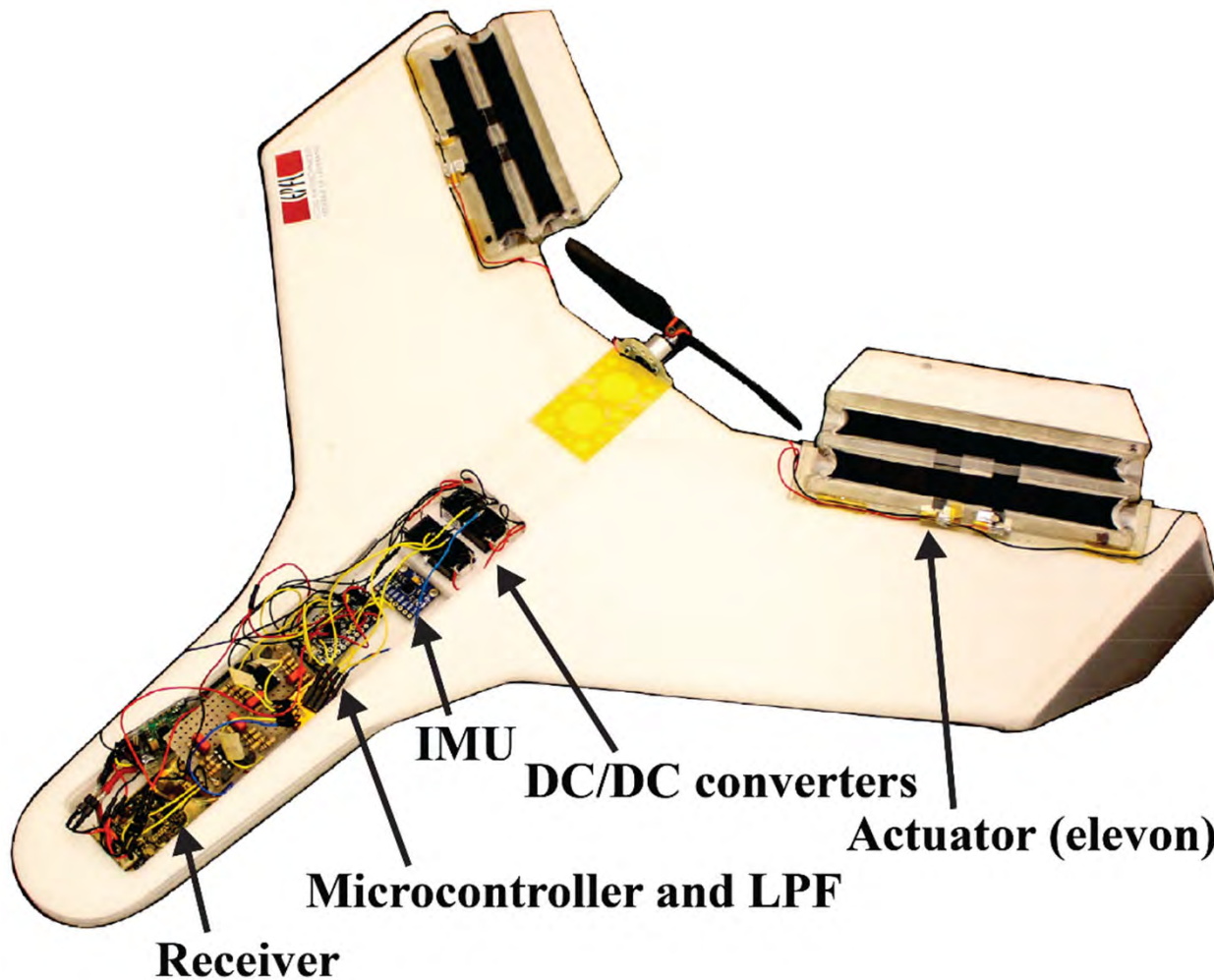


Flying robot with foldable actuators

Foldable function enables shape change of robots to improve portability



Wireless input signals are converted to high voltage within the robot to drive the actuators

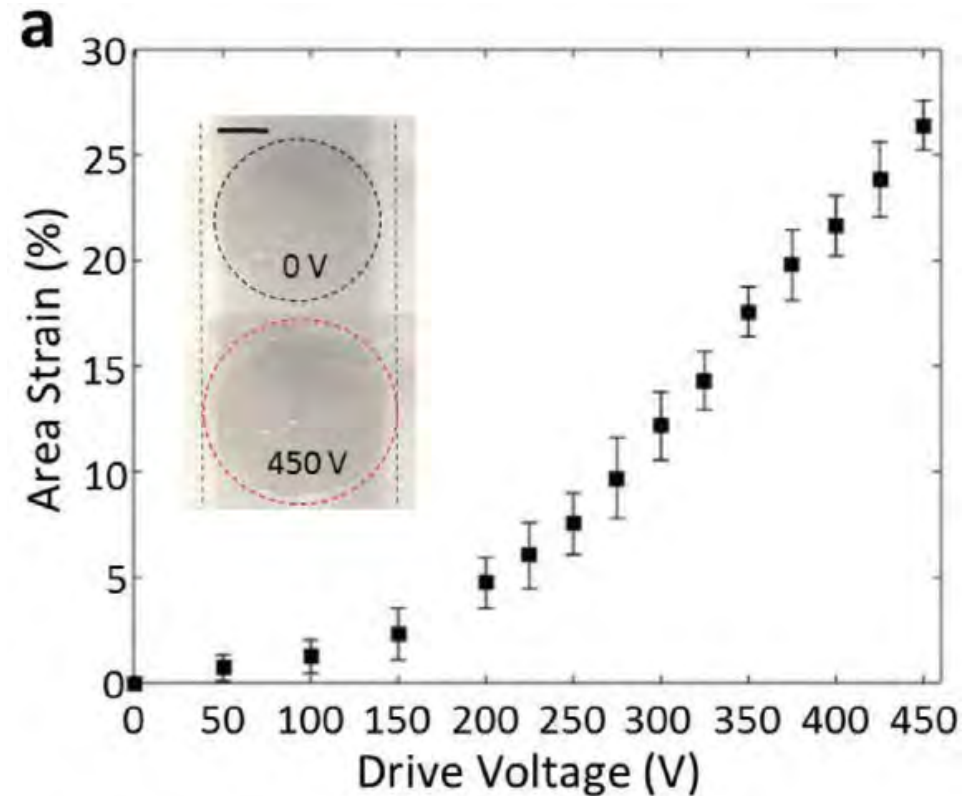
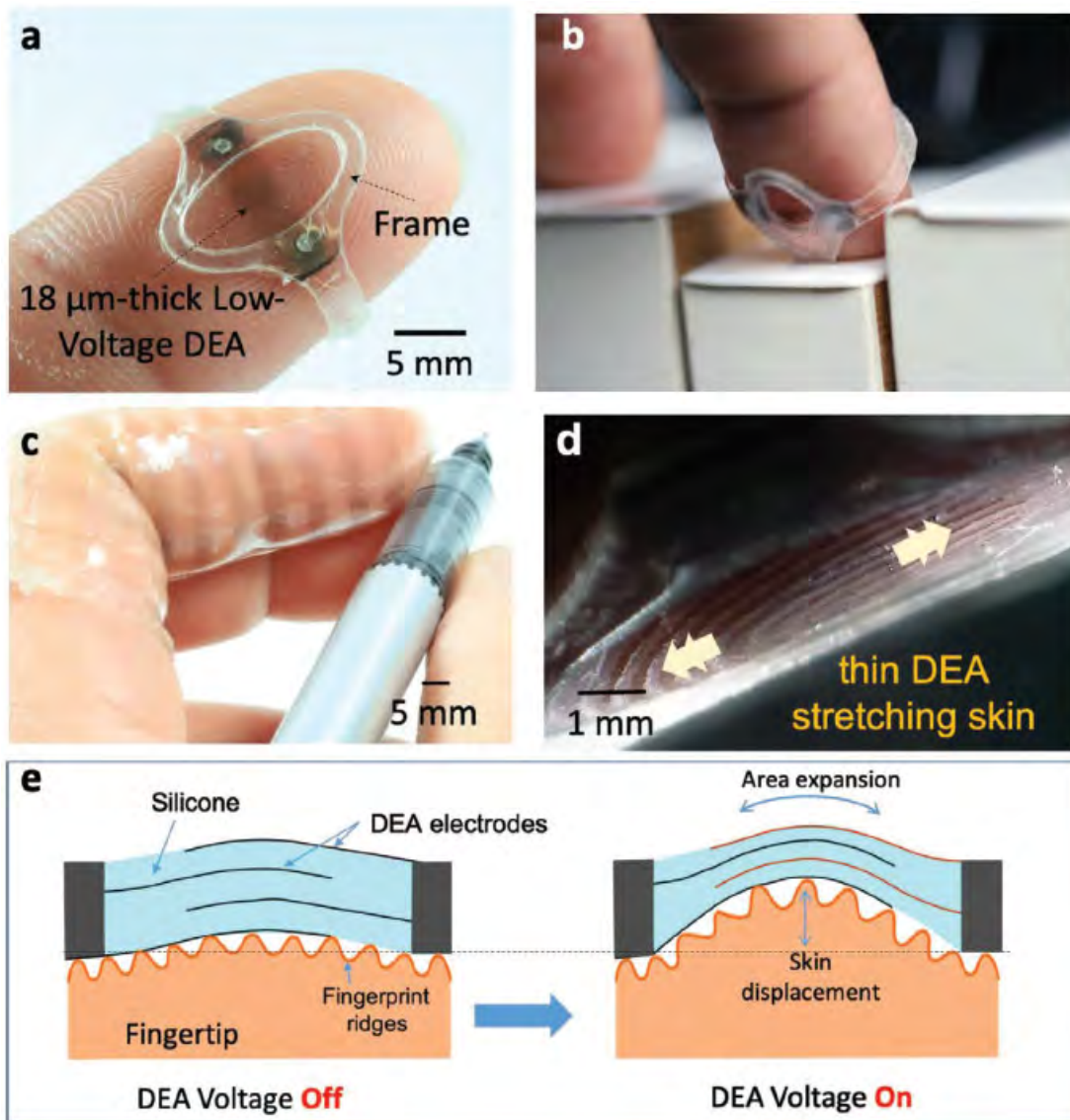


Each DC/DC converter weighs 4.2 g (0-5000V output)



Examples from other studies

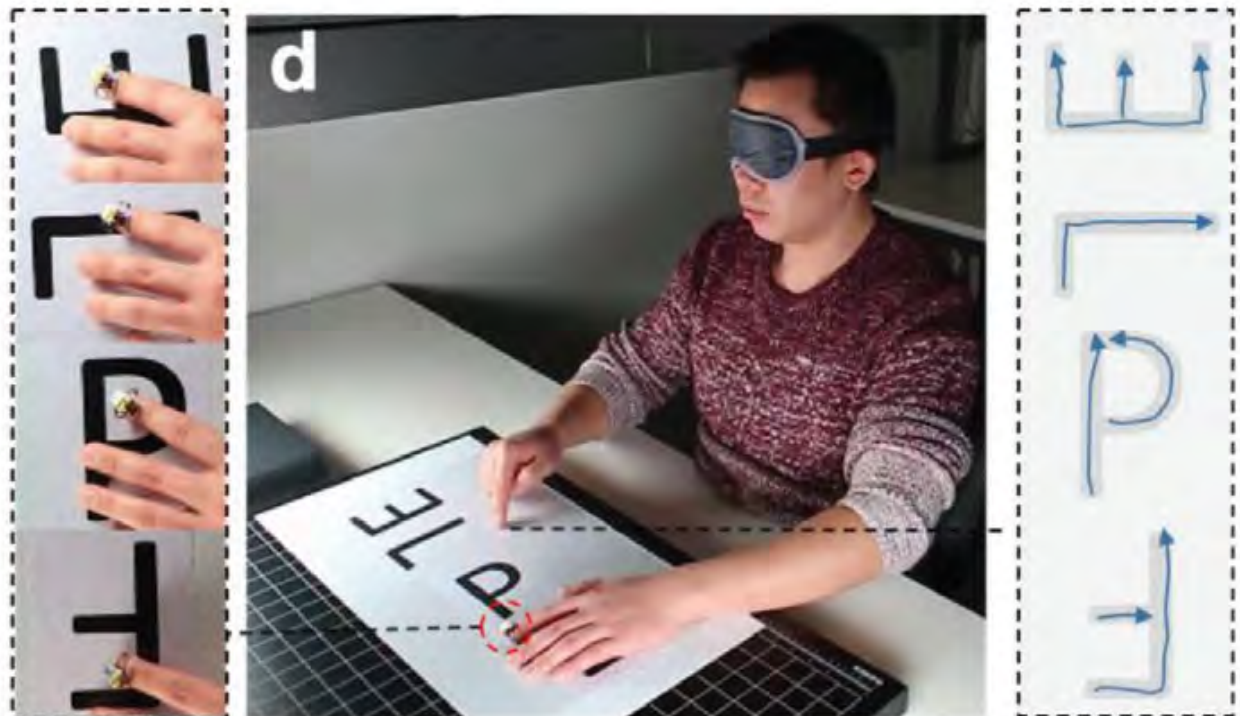
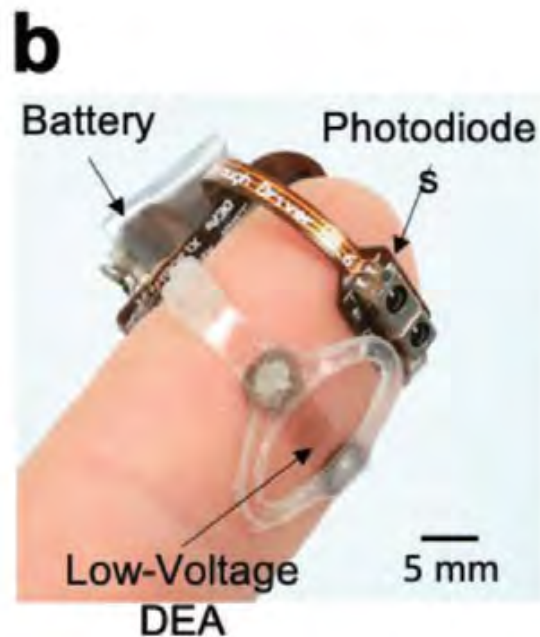
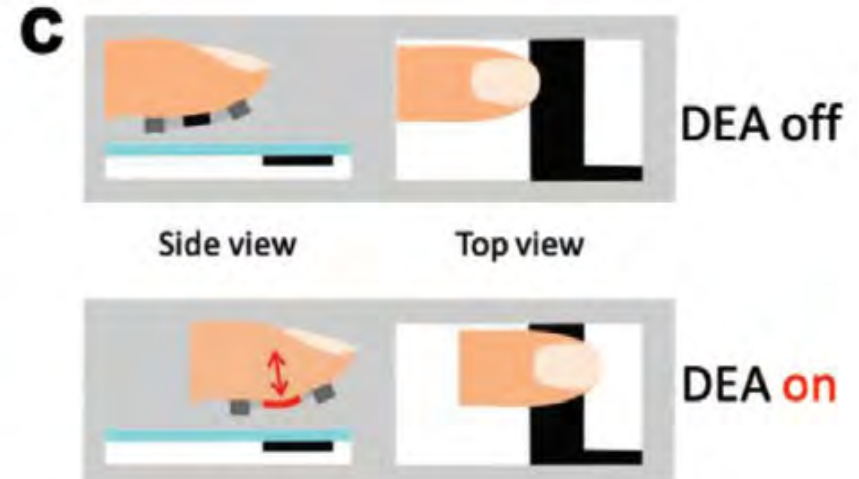
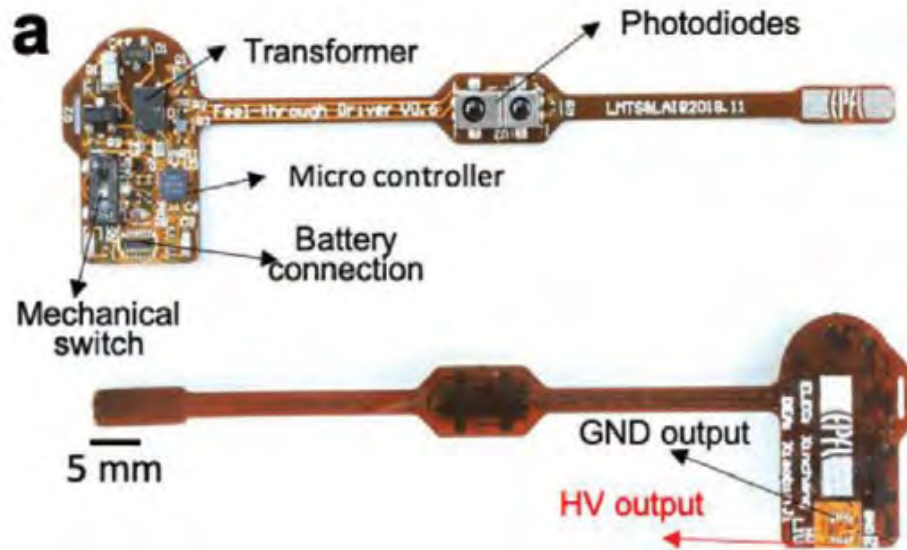
CNT electrode applied on 18 μm film and actuated up to 500 Hz at 450 V



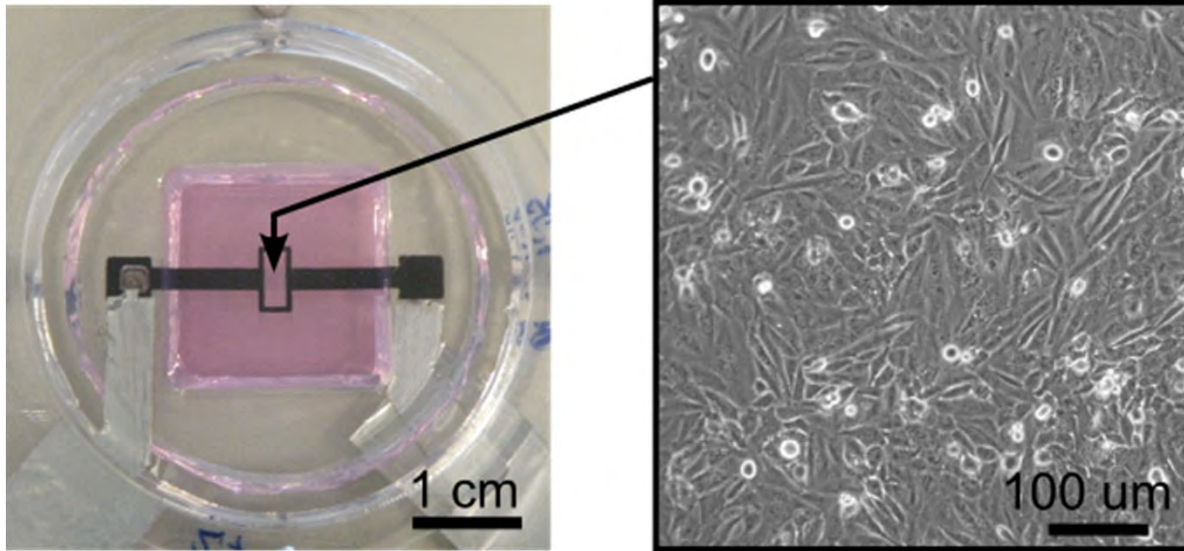
Ji, Xiaobin, et al. "Untethered Feel-Through Haptics Using 18- μm Thick Dielectric Elastomer Actuators." *Advanced Functional Materials*: 2006639.

Examples from other studies

Ji, Xiaobin, et al. "Untethered Feel-Through Haptics Using 18- μm Thick Dielectric Elastomer Actuators." *Advanced Functional Materials*: 2006639.

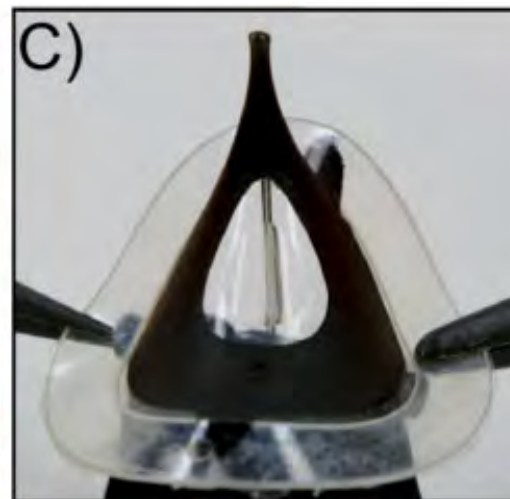
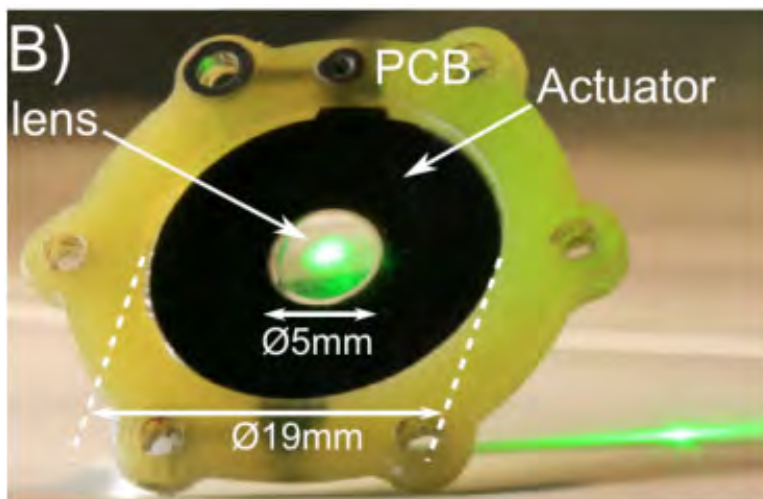


Examples from other studies



Poulin, Alexandre, et al. "An ultra-fast mechanically active cell culture substrate." *Scientific reports* 8.1 (2018): 1-10.

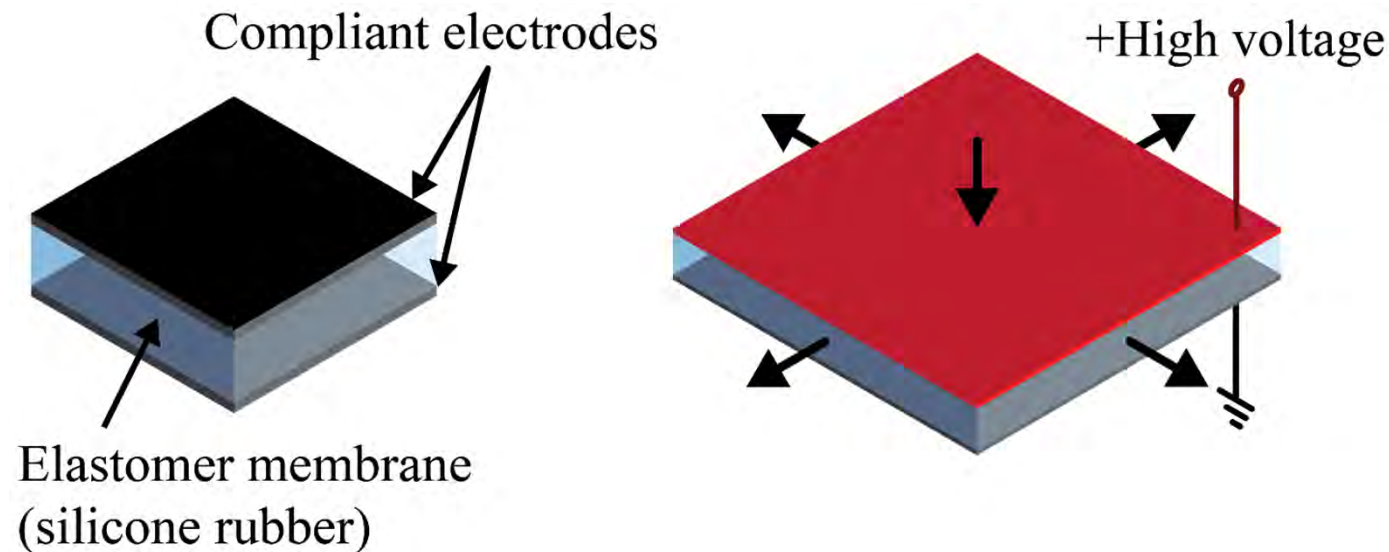
Device to measure mechanical properties of living cells



Maffli, Luc, et al. "Ultrafast all-polymer electrically tunable silicone lenses." *Advanced functional materials* 25.11 (2015): 1656-1665.

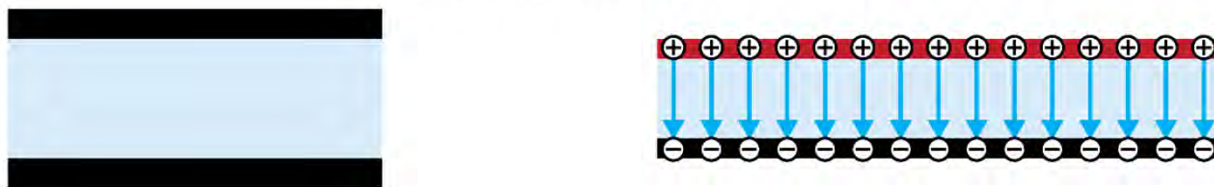
Soft lens

Dielectric elastomer actuators (DEAs)



- **Simple**
- **Soft (elastic modulus is ~ 1 MPa)**
- **Fast (can be actuated at ~ 1 kHz)**
- **Large actuation strain (~ 100 % linear stroke)**
- **High voltage (a few kV)**
- **Self-sensing**

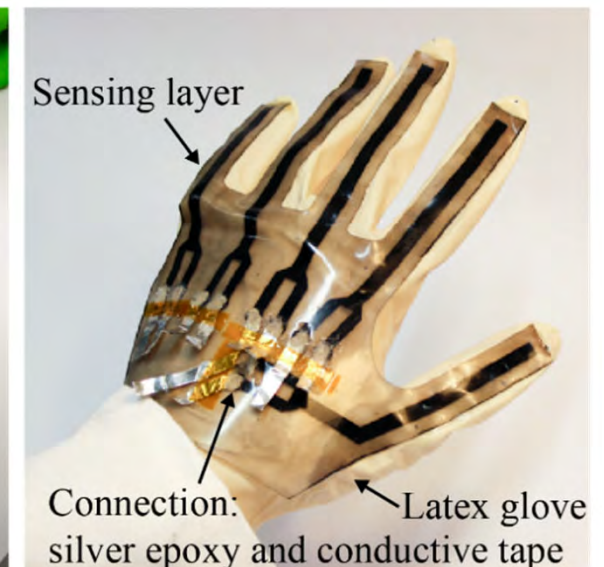
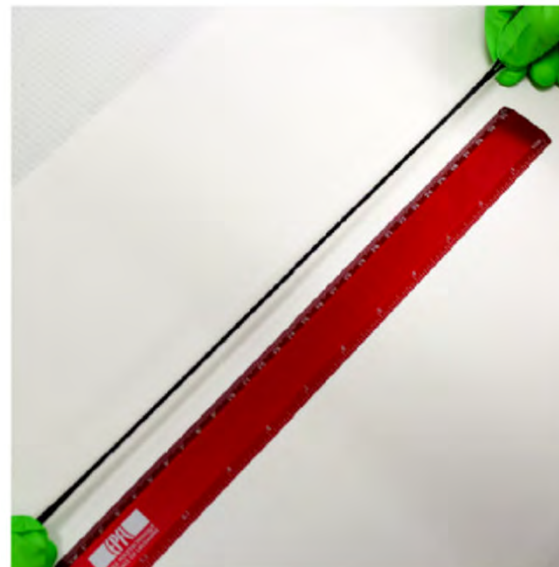
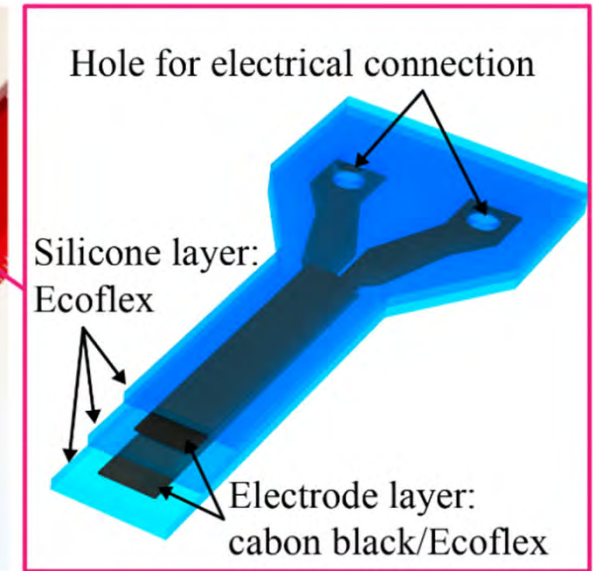
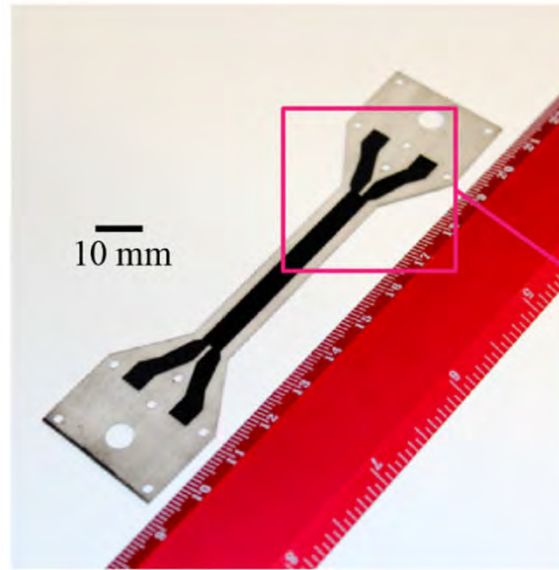
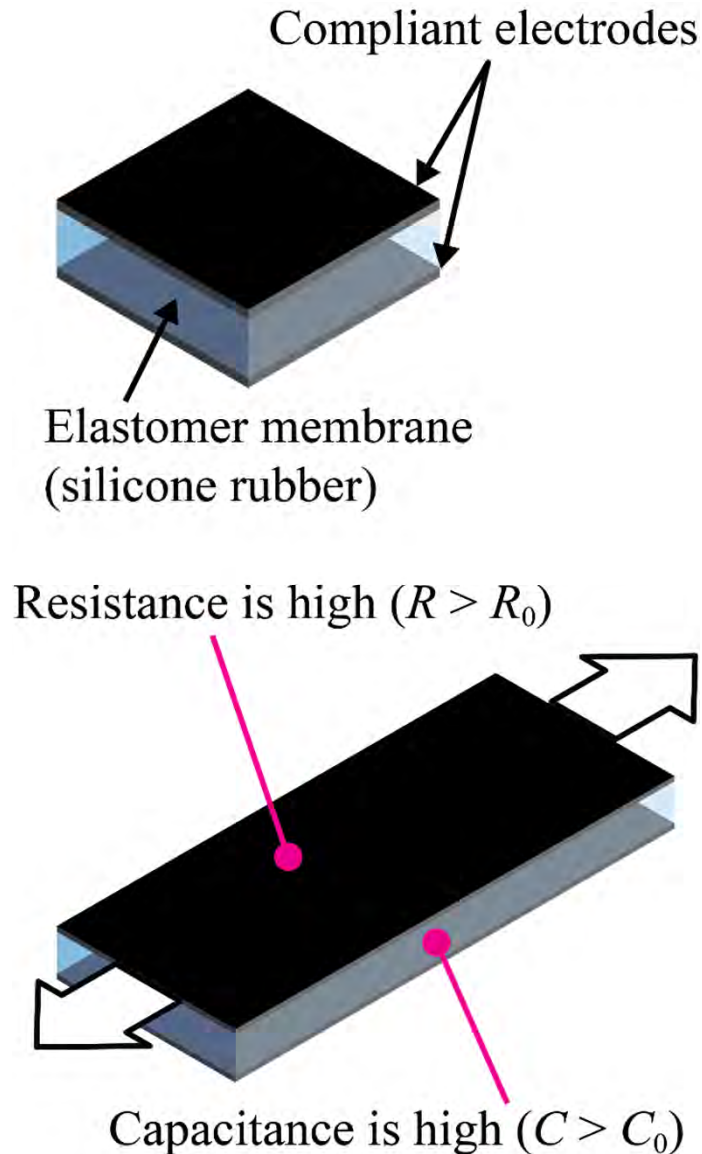
Cross-section



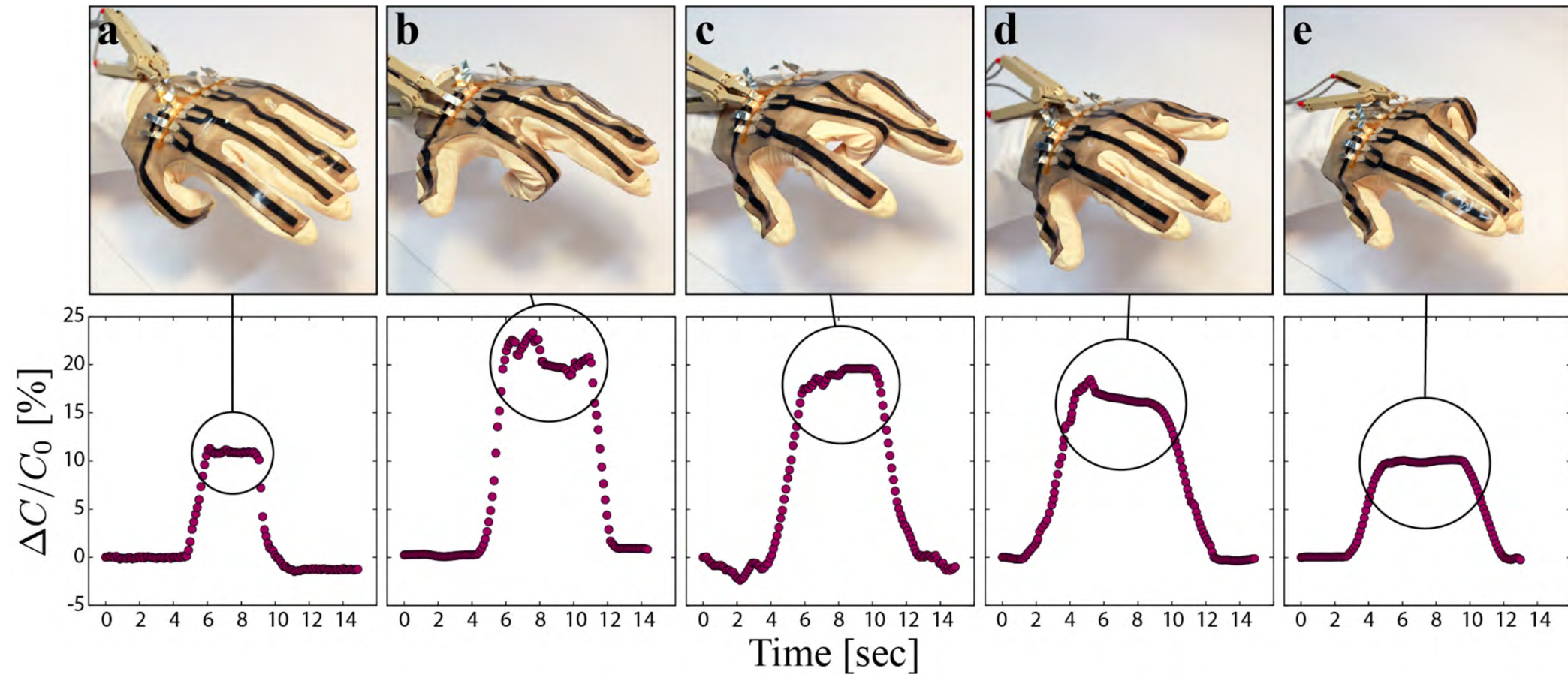
← Electric field ■ High voltage ■ Ground

Sensing aspect of DEAs:

Wearable sensors capable of detecting strains 500%



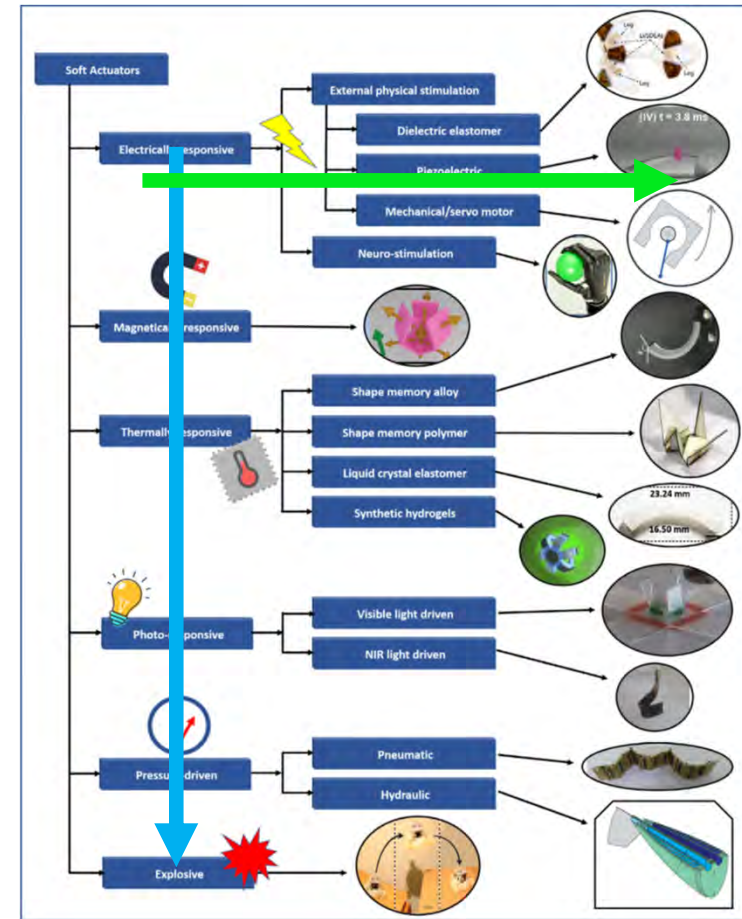
Demonstration of intelligent glove with distributed sensors



Aim of the topic “Soft Actuators”

11/14: Detail a single soft actuator technology and describe how it enables various actuator configurations and robotic systems.

11/21: Overview existing soft actuators and discuss their pros and cons, followed by homework.

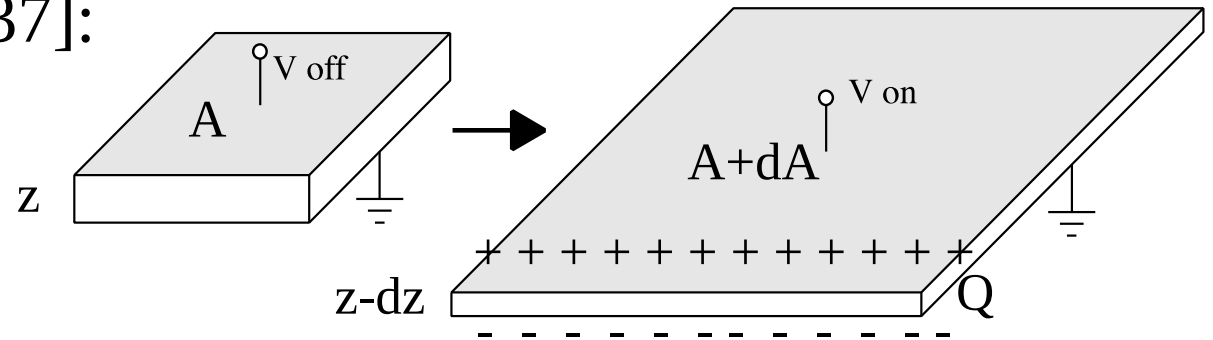


El-Atab, Nazek, et al. "Soft actuators for soft robotic applications: A review." *Advanced Intelligent Systems* 2.10 (2020): 2000128.

Appendix

DEA Theory

- Electrostatic Pressure [37]:



Capacitance: $C = \frac{\epsilon_0 \epsilon A}{z}$ (1)

ϵ_0 = permittivity of free space
 ϵ = relative permittivity

Energy: $U_e = \frac{1}{2} \frac{Q^2}{C} = \frac{1}{2} \frac{zQ^2}{\epsilon_0 \epsilon A}$ (2)

Change in energy:

change in electrical energy electrical to mechanical conversion of energy (work)

$$dU_e = \frac{Q}{C} dQ + U_e \left\{ \left(\frac{1}{z} \right) dz - \left(\frac{1}{A} \right) dA \right\} = \boxed{V dQ} + \boxed{U_e \left\{ \left(\frac{1}{z} \right) dz - \left(\frac{1}{A} \right) dA \right\}}$$
 (3)

DEA Theory

- Electrostatic Pressure [37 ch. 1]:

Constant volume assumption: $Az = Vol \Rightarrow dVol = A dz + z dA = 0$ (4)

Simplifying (3): $dU_e = V dQ - 2U_e \left(\frac{1}{A} \right) dA = V dQ + 2U_e \left(\frac{1}{z} \right) dz$ (5)

Compressive stress p is defined as:

$$-Ap dz = dW \Rightarrow p = \left(\frac{1}{A} \right) \frac{dU_e}{dz} \quad (\text{constant charge}) \quad (6)$$

Substituting (5) with $dQ=0$ into (6) and simplifying:

$$p = \epsilon_0 \epsilon \left(\frac{V}{z} \right)^2 = \epsilon_0 \epsilon E^2$$

 Electrostatic pressure
(Maxwell stress) (7)

DEA Theory

- Strain [37 ch. 1]:
 - Unloaded film with free boundary conditions.

Strain in z:
$$S_z = -\frac{p}{Y} = -\frac{\varepsilon_0 \varepsilon}{Y} E^2 = -\frac{\varepsilon_0 \varepsilon}{Y} \left(\frac{V}{z} \right)^2 \quad Y = \text{Young's modulus} \quad (8)$$

Where z:
$$z = z_0 (1 + S_z) \quad z_0 = \text{initial thickness} \quad (9)$$

Note, for small strains: $z \approx z_0$

Substituting (8) into (9):
$$S_z^3 + 2S_z^2 + S_z = -\frac{\varepsilon_0 \varepsilon}{Y} \left(\frac{V}{z_0} \right)^2 = m \quad (10)$$

The real solution to (10):
$$S_z = -\frac{2}{3} + \frac{1}{3} \left(H + \frac{1}{H} \right) \quad (11)$$

$$H = \left[\frac{1}{2} \left\{ 2 + 27m + \left(-4 + (2 + 27m)^2 \right)^{1/2} \right\} \right]^{1/3} \quad (12)$$

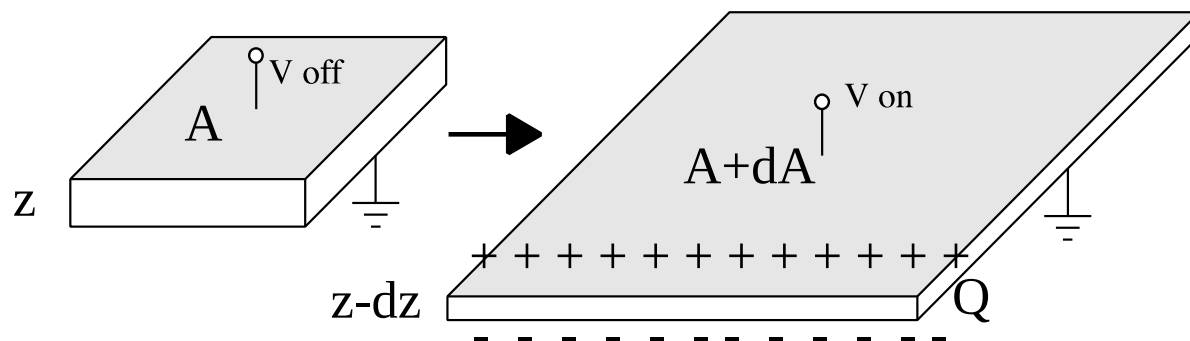
DEA Theory

- Strain [37 ch. 1]:
 - Unloaded film with free boundary conditions.

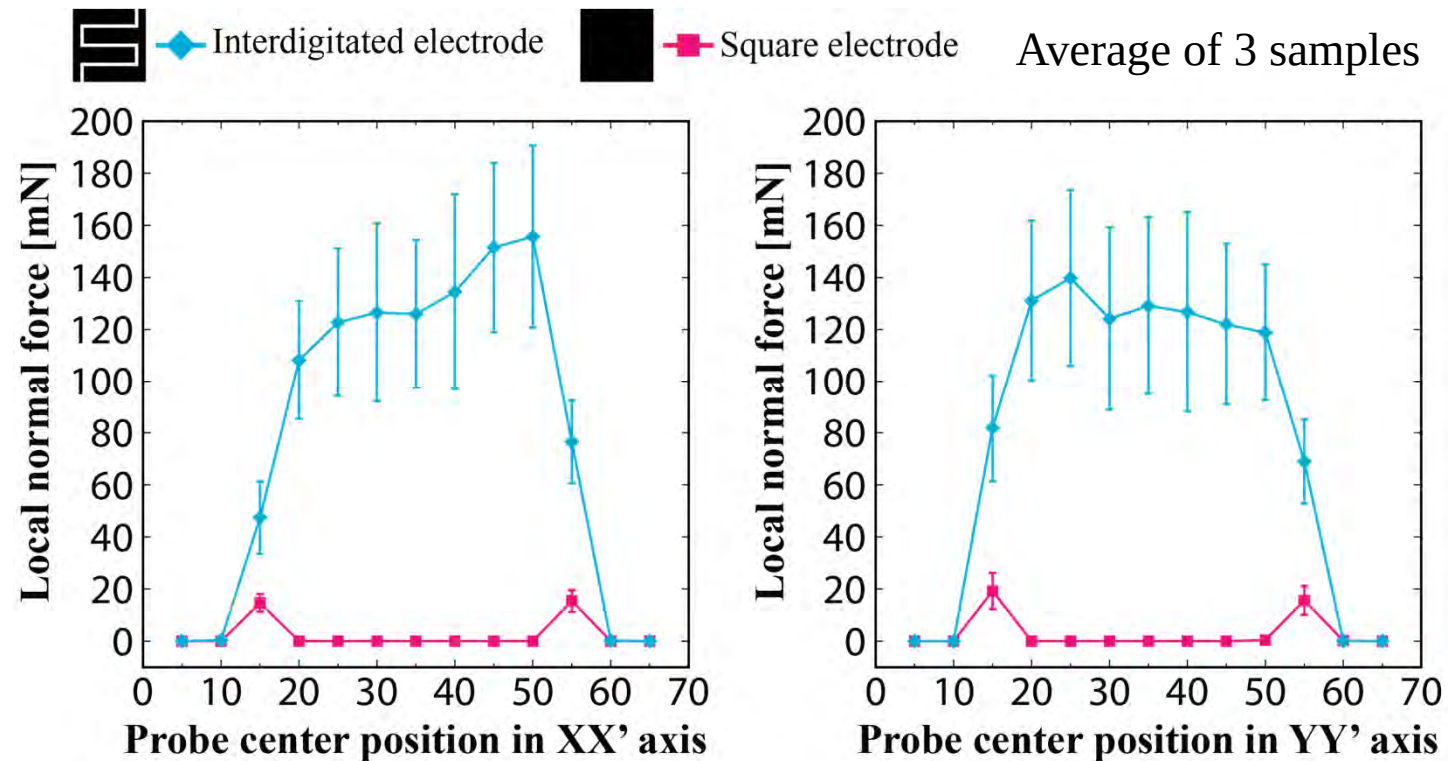
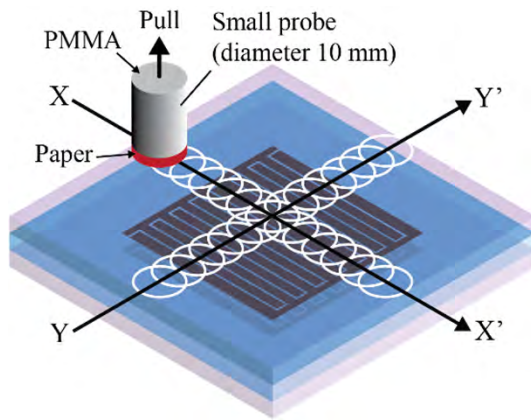
Strain in all directions (constant volume): $(1 + S_x)(1 + S_y)(1 + S_z) = 1$ (13)

If, $S_x = S_y = S_a$ then, $S_a = (1 + S_z)^{-1/2} - 1$ (14)

and $S_z = -\frac{S_a^2 + 2S_a}{S_a^2 + 2S_a + 1}$ (15)



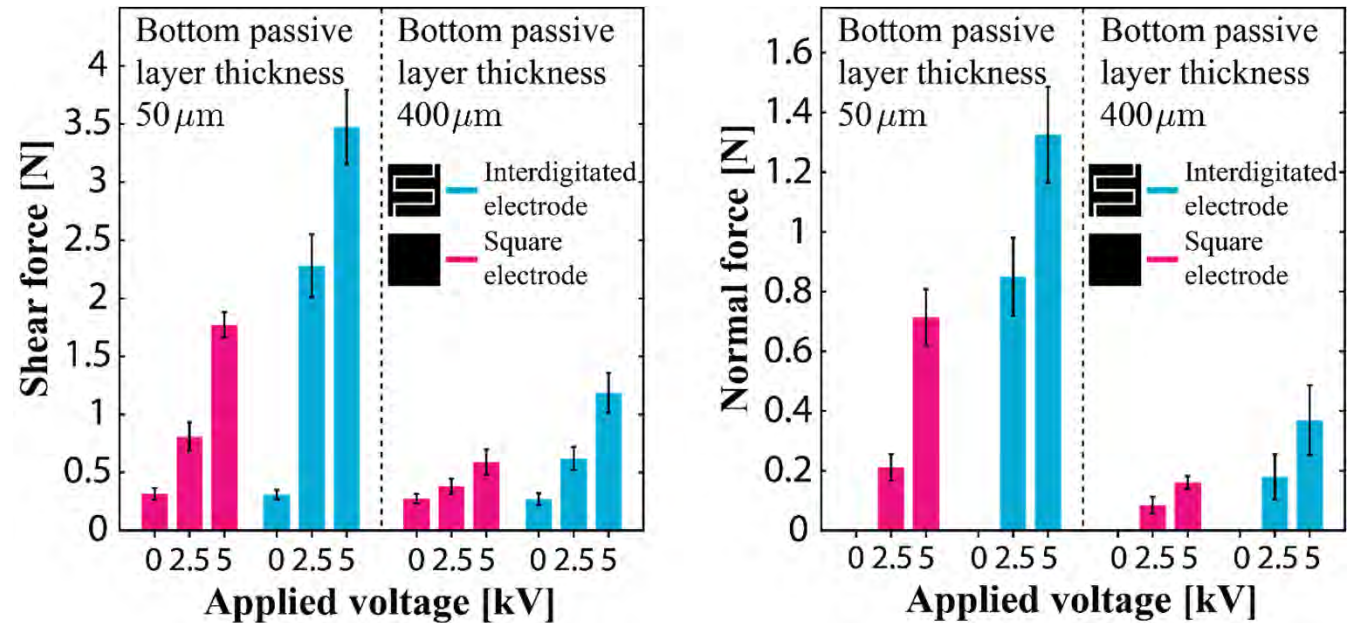
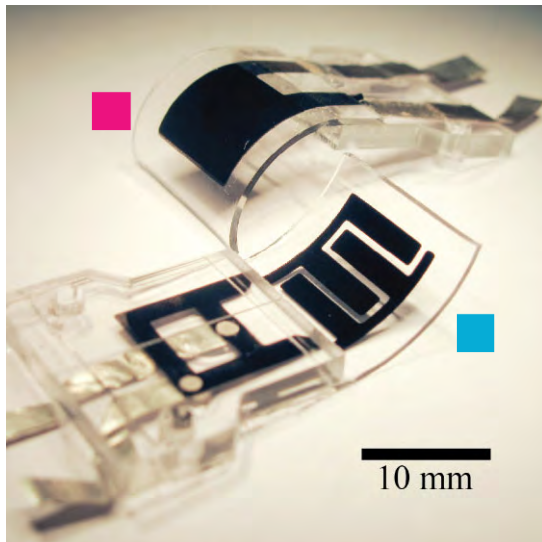
Interdigitated electrode geometry generates homogeneous, large adhesion force 10 times higher than the square geometry



Interdigitated electrode: adhesion force $\propto$ area, ~ 2400 mN total
Square electrode: adhesion force $\propto$ periphery, ~ 240 mN total

Newton order electroadhesion force represents high holding force of the gripper

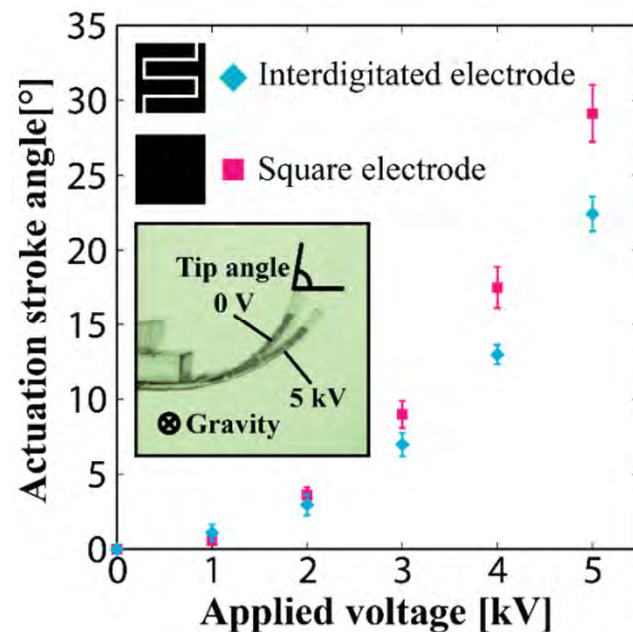
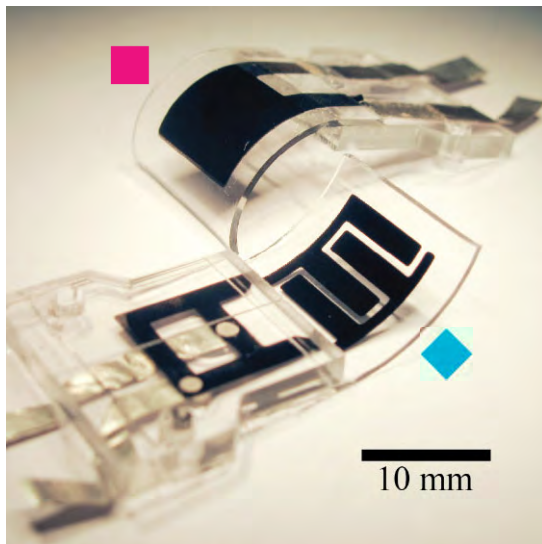
Average of 4 samples



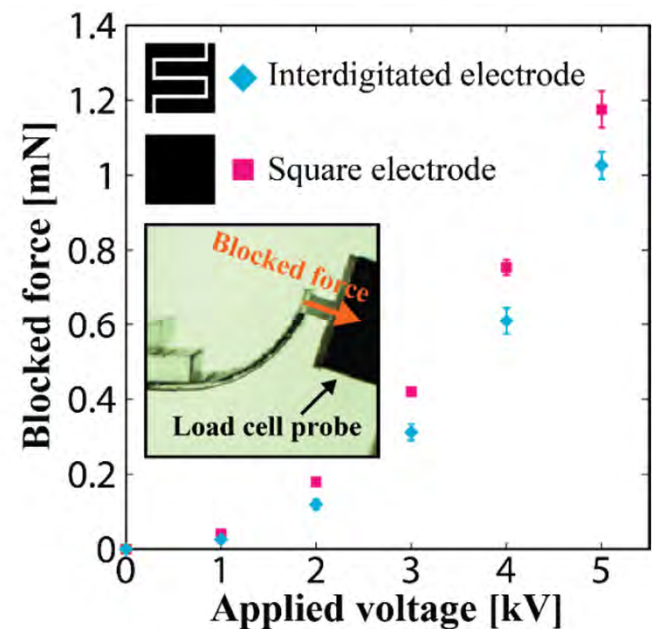
Shear force at 5 kV: 3.5 N for the interdigitated, 1.8 N for the square

- Force difference between the two electrode geometry corresponds to the edge length.
- Larger thickness results in reduced force.
- Normal force shows trend similar to the shear force.

Interdigitated electrode shows only 20 % reduction of the actuator performance compared to the square geometry

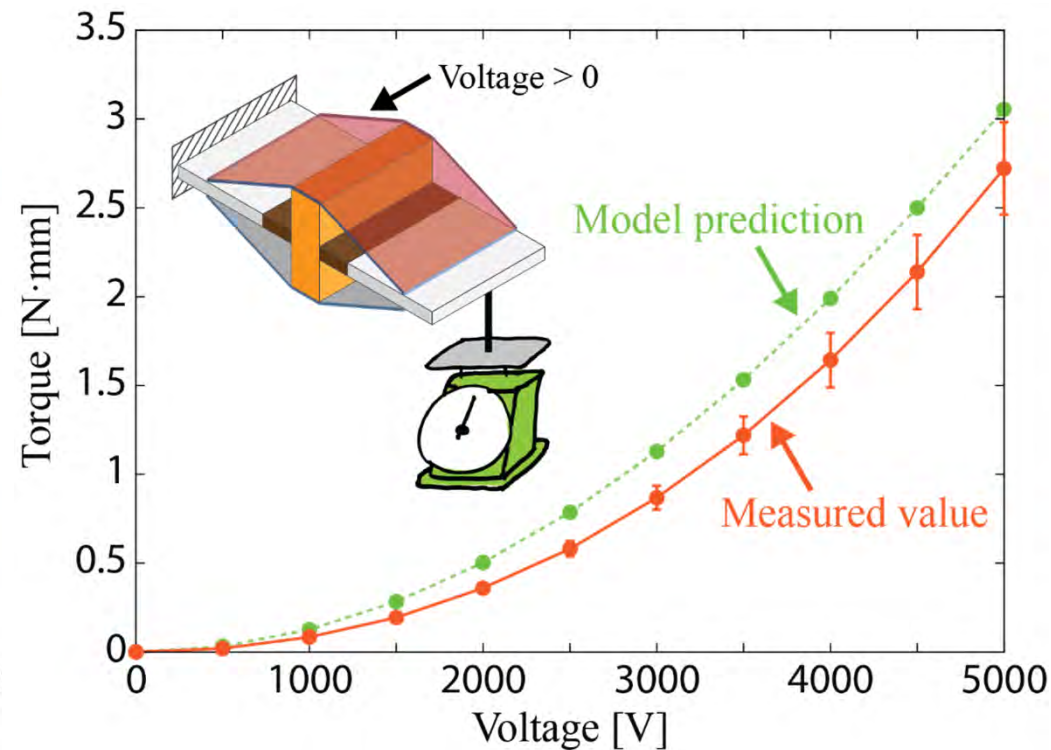
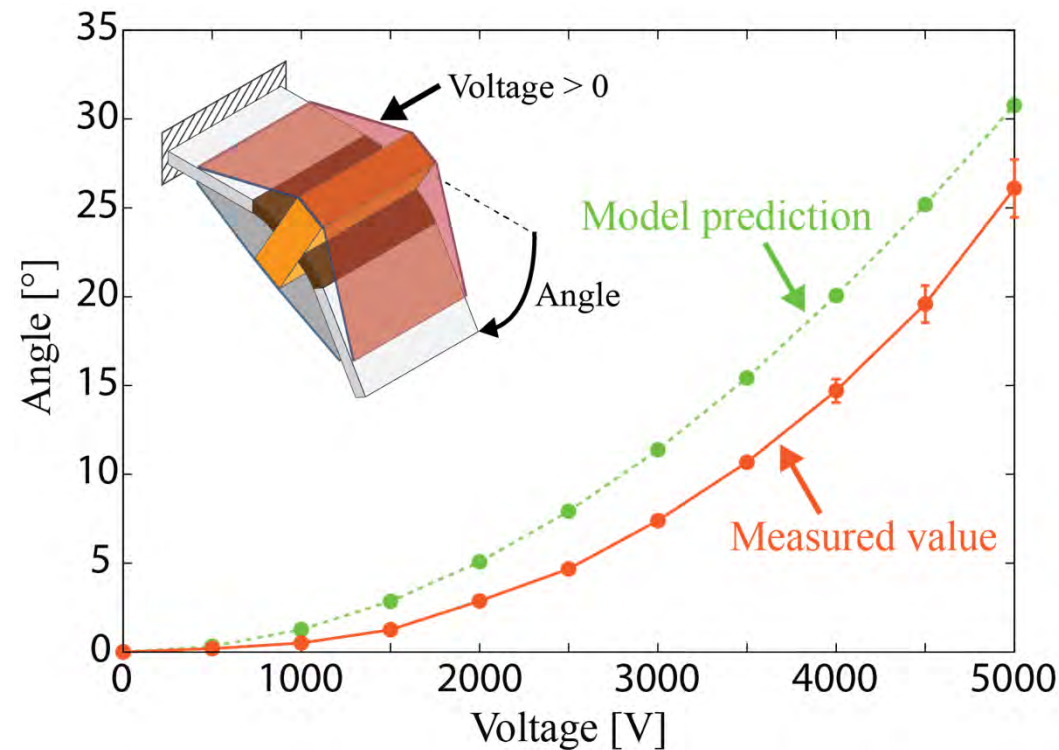
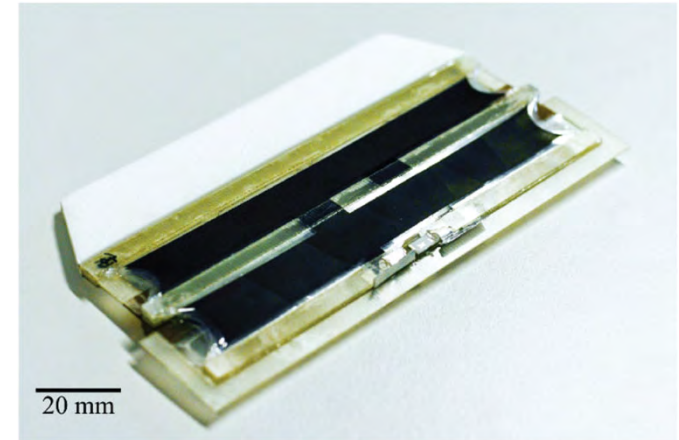


Average of 4 samples



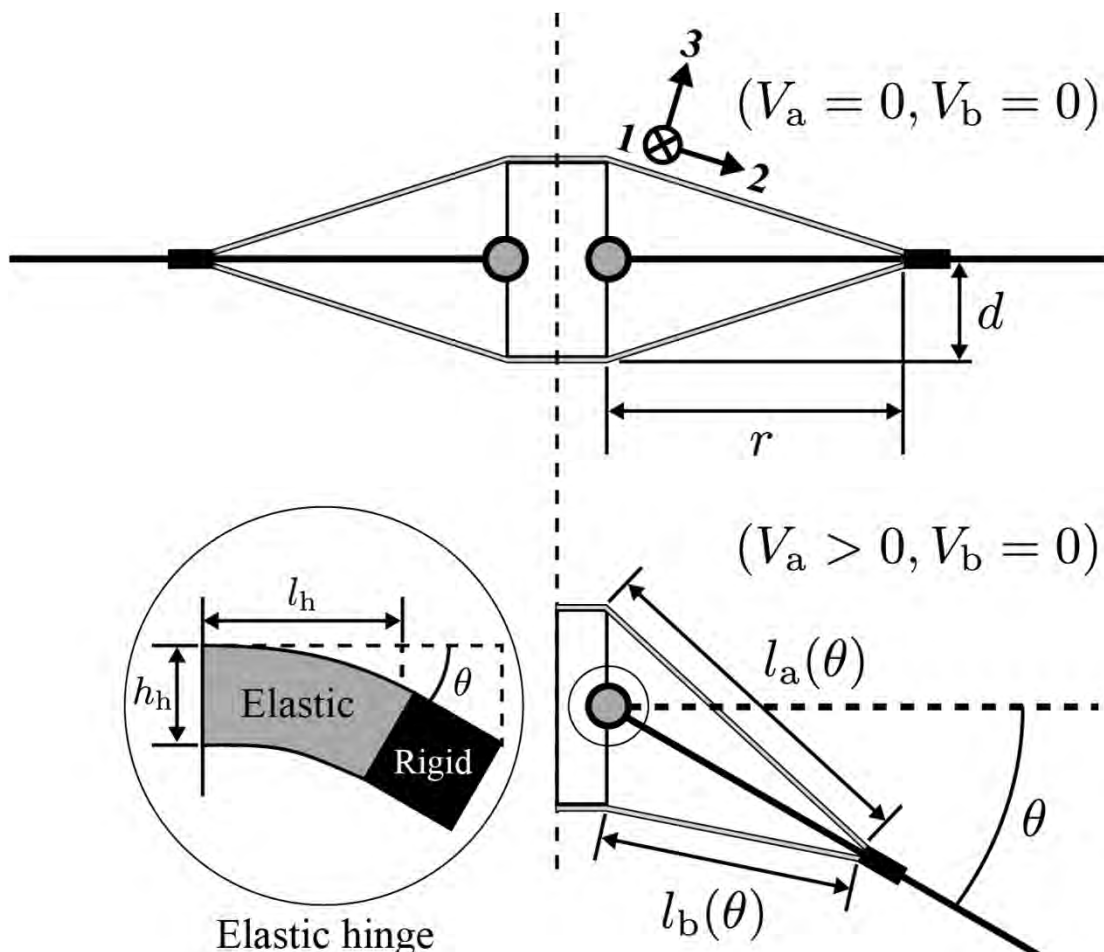
- Actuation stroke at 5 kV: 22 ° for the interdigitated, 29 ° for the square
- Blocked force at 5 kV: 1 mN for the interdigitated, 1.2 mN for the square
- mN order force enables handling of fragile and sensitive objects in the gripper.

Actuator angle and torque can be controlled and predicted



Analytical model to calculate the bending angle and the torque

$$U_{\text{tot}} = U_{\text{strain}_a} + U_{\text{strain}_b} + U_{\text{electric}_a} + U_{\text{electric}_b} + U_{\text{hinge}},$$

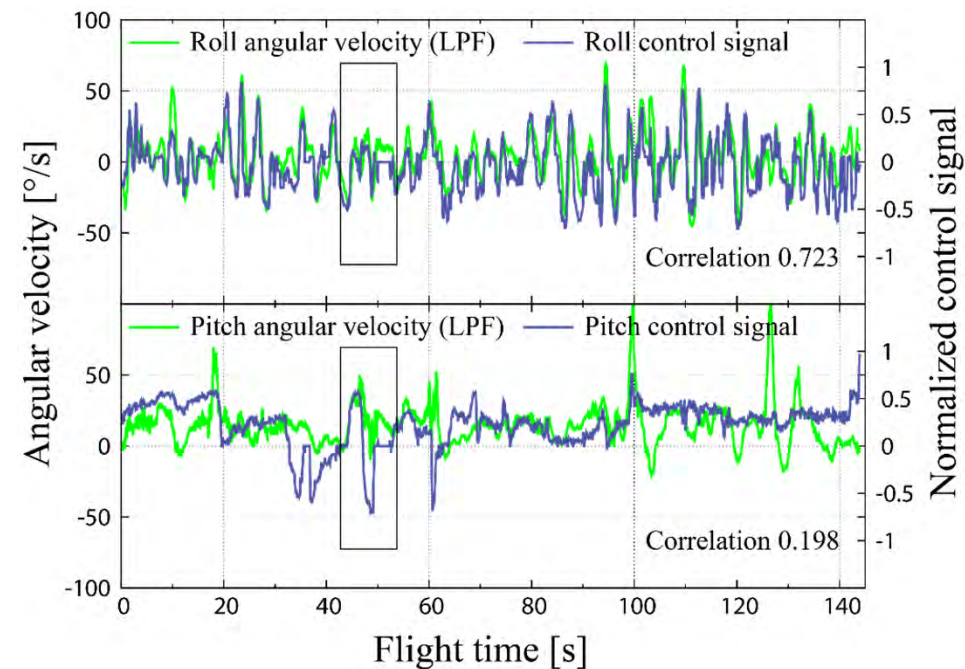
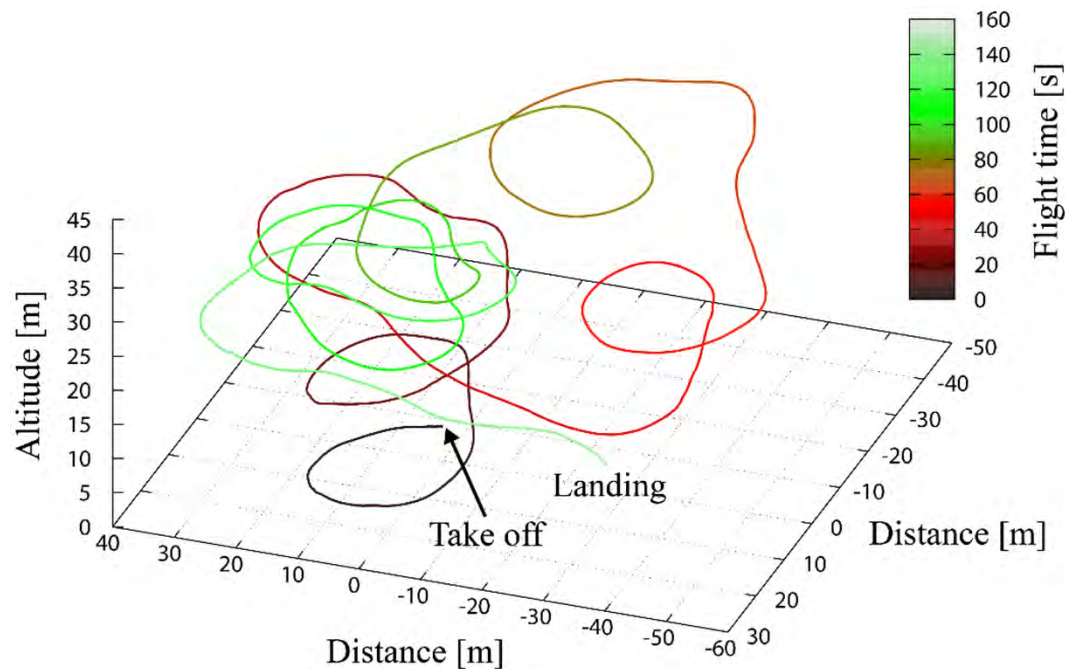
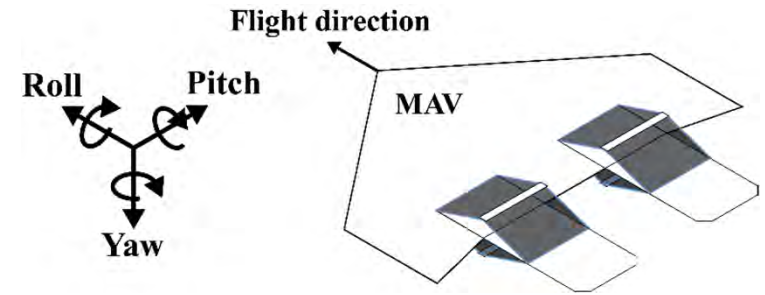


$$W = \sum_{i=1}^3 C_i (I_1 - 3)^i,$$

$$p = -\epsilon_0 \epsilon_r \frac{V^2}{z^2} = -\epsilon_0 \epsilon_r E^2$$

$$\frac{\partial U_{\text{tot}}}{\partial \theta} = 0, \text{ and } \frac{\partial^2 U_{\text{tot}}}{\partial \theta^2} > 0,$$

The foldable actuators well controlled the drone



The result shows the foldable actuators are useful for robotic applications.

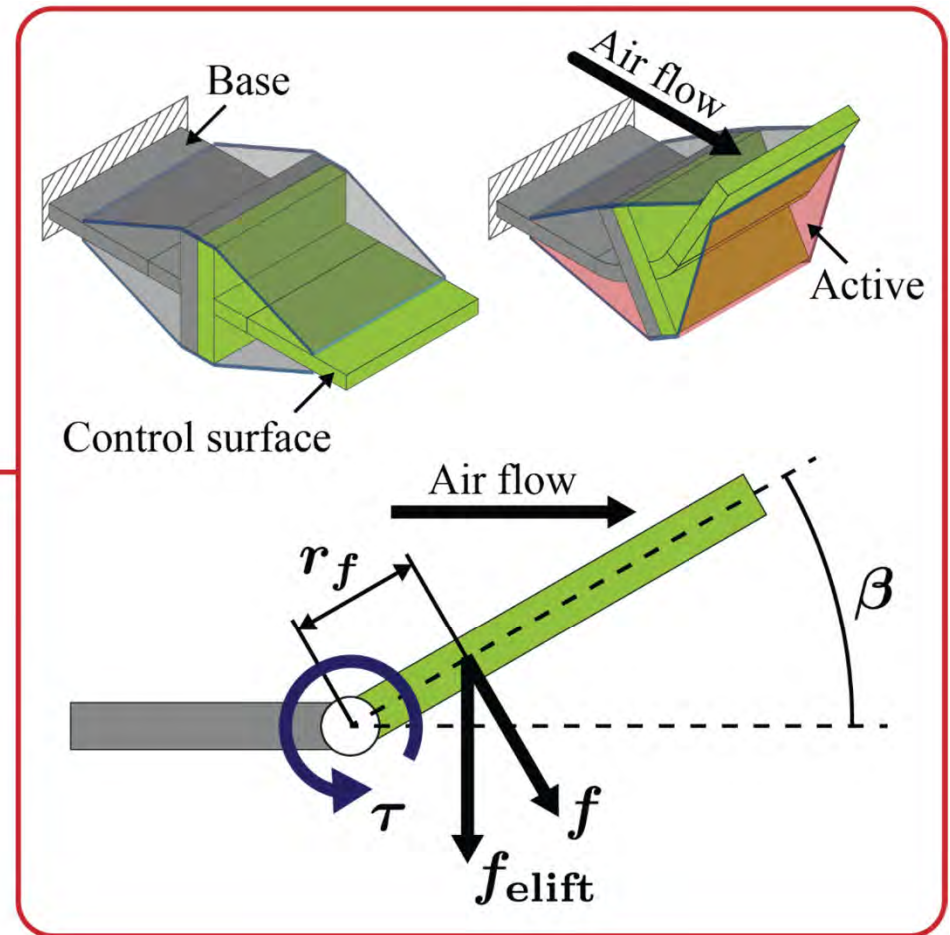
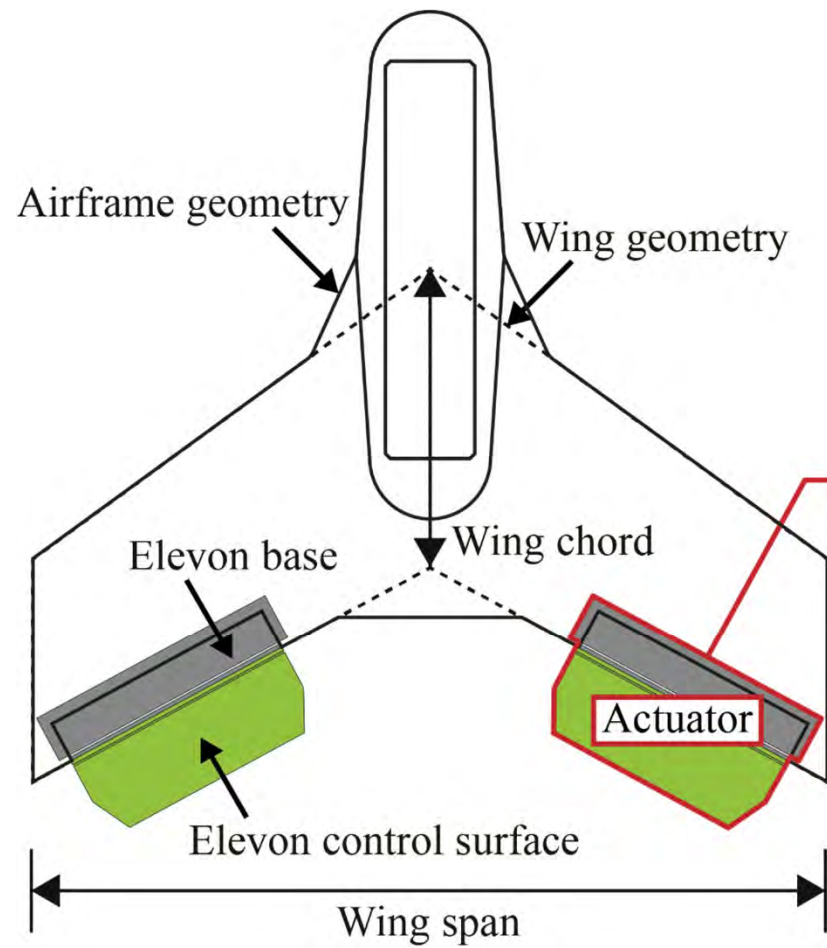


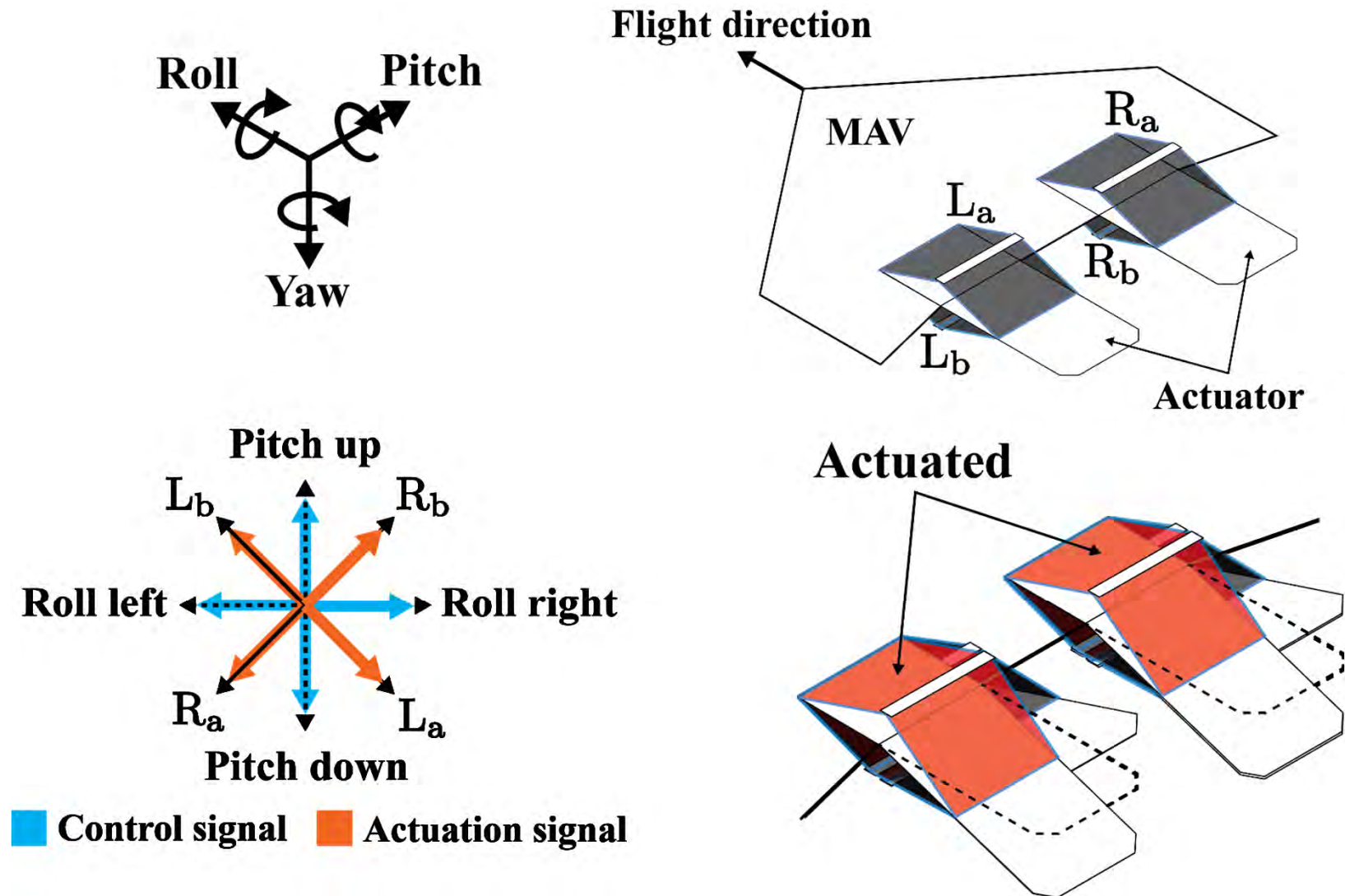
Table 4.1 – Design parameter and specifications of the elevon actuator

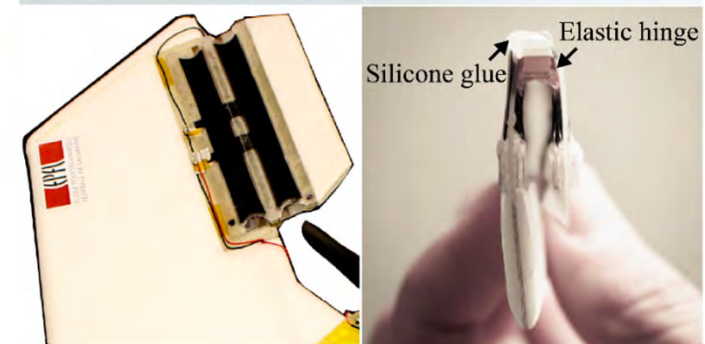
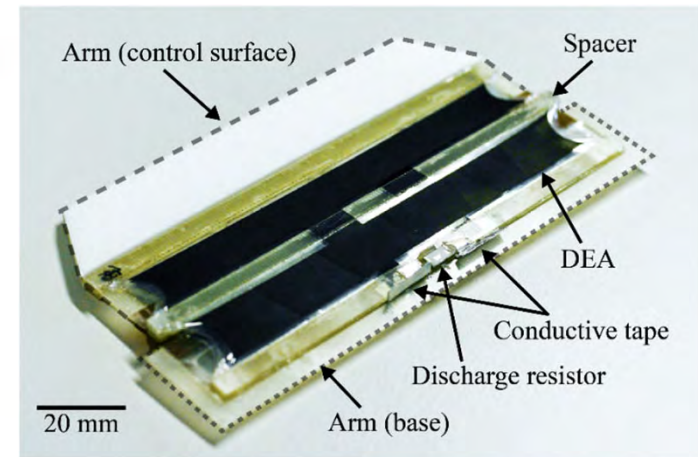
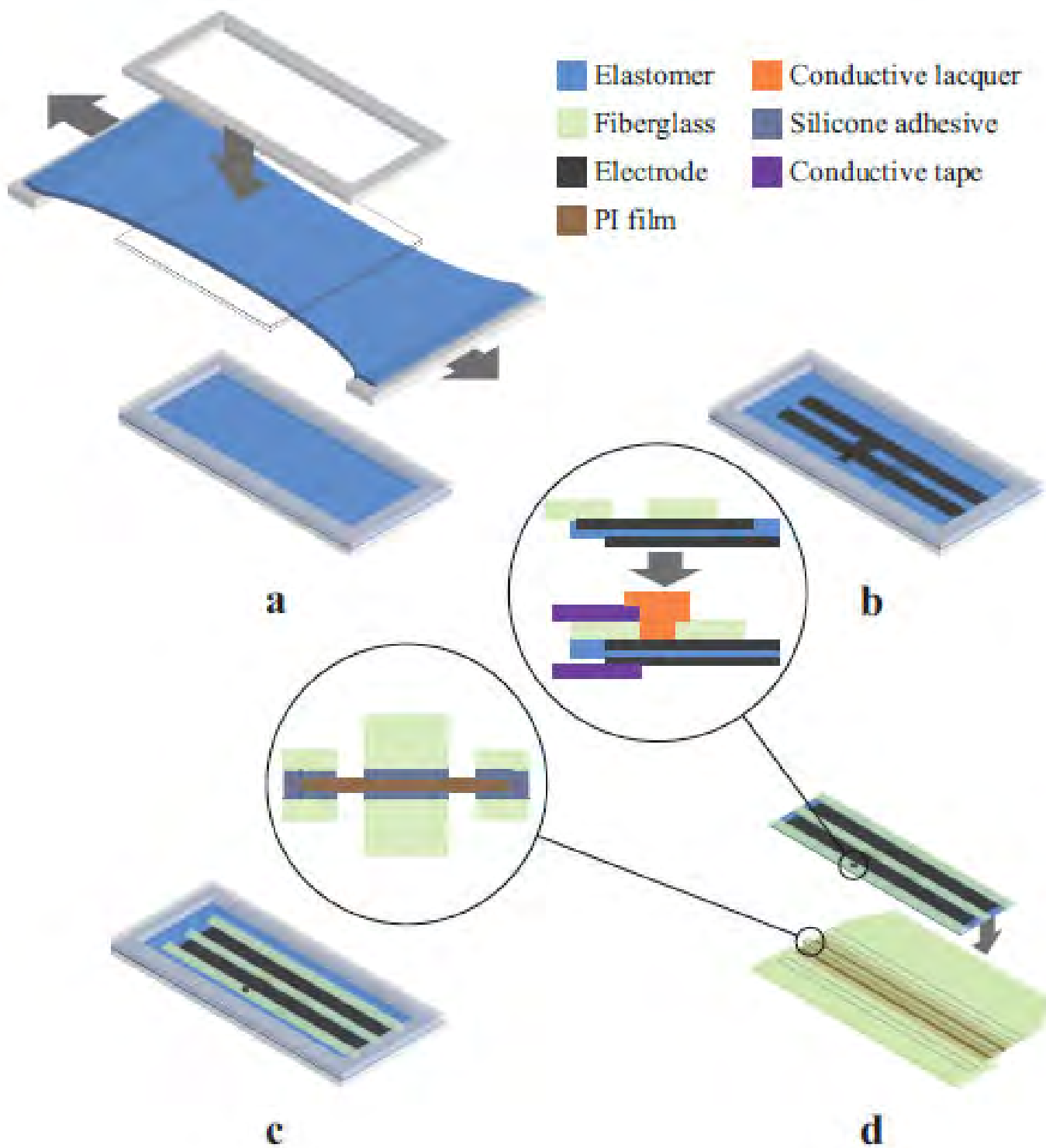
Design parameter	Value
Dimensions	
DEA (half part)	
Initial length l_0	14.1 mm
Initial width w_0	60 mm
Initial thickness h_0	125 μm
DEA electrode (half part)	
Initial length l_{e0}	11.3 mm
Width w_e	112 mm
Frame	
Arm length r	14.5 mm
Spacer height d^{*1}	1.840 mm (1 DEA) 2.025 mm (2 DEAs)
Spacer area (length $\times$ width)	4 mm $\times$ 120 mm
Elastic hinge	
Length l_h	1.0 mm
Width w_h	120 mm
Thickness h_h	50 μm
Silicone adhesive film	
Thickness	40 μm
Material property	
DEA elastomer	
Relative permittivity ϵ_r	2.8 [233],[244]
Material constant C_1	0.105 MPa
Material constant C_2	0.00332 MPa
Material constant C_3	1.44×10^{-13} MPa
Elastic hinge	
Elastic modulus E_h^{*2}	9.1 GPa
Other parameter	
Pre-stretch ratio λ_{1p}	2.0
Permittivity of free space ϵ_0	8.85×10^{-12} F/m
Specifications	
Mass	14.4 g
Base area (length $\times$ width)	24 mm $\times$ 130 mm
Control surface area (length $\times$ width)	40 mm $\times$ 120 mm

Table 4.2 – Specifications of the MAV

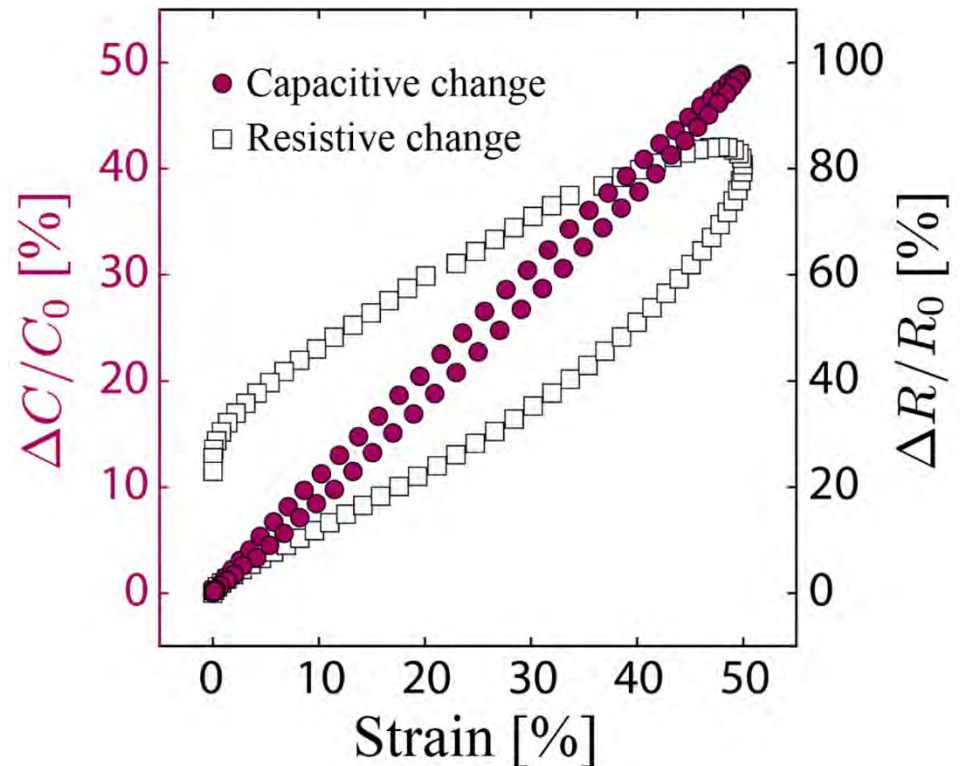
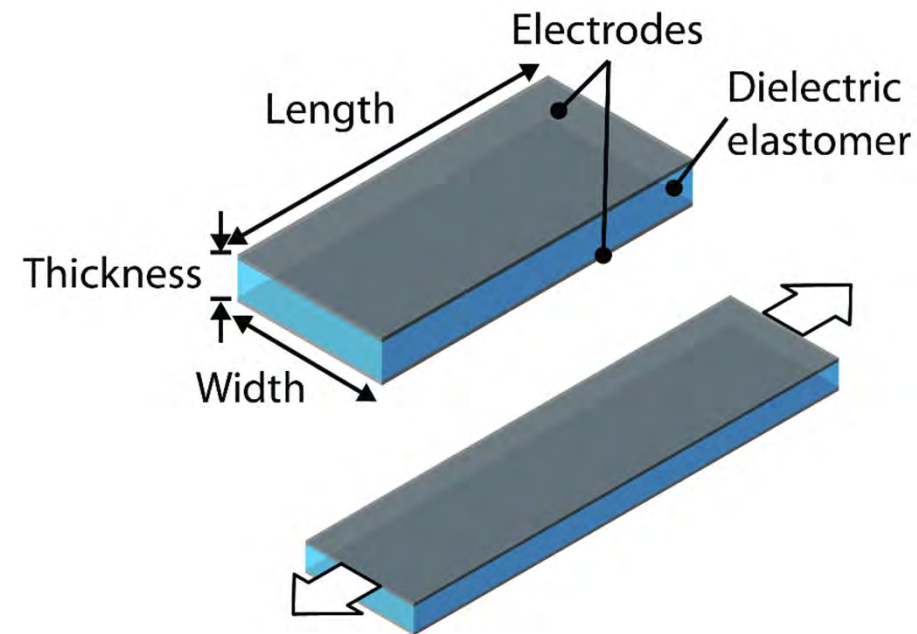
Specification	Value
Dimensions	
Wing span	400 mm
Wing chord	150 mm
Wing area S	0.0525 m ²
Elevon surface area S_e	0.0043 m ²
Elevon aerodynamic force position r_f	10.7 mm
Other	
Angle of attack of the wing α	7.5 °
Maximum elevon angle β	15 °
Measured mass	130.7 g
Estimated flight speed V based on m	6.14 m/s
Estimated required torque τ	1780 mN $\cdot$ mm

Actuation combination of 4 DEAs provides pitch and roll attitude control





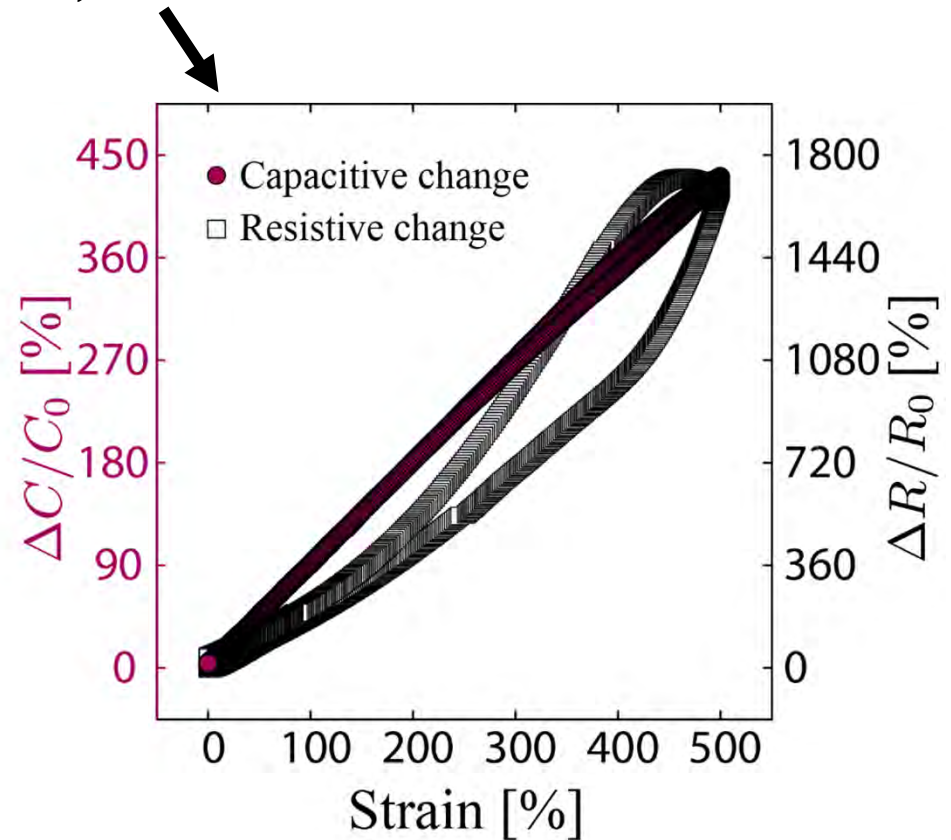
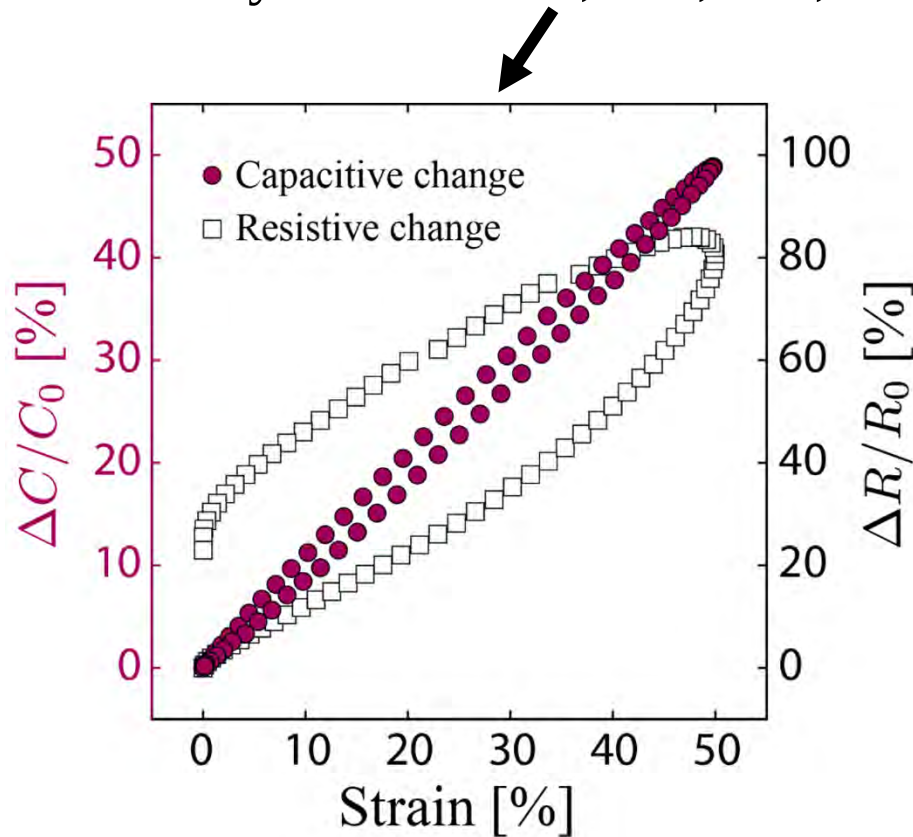
One way of using DEA structure as sensor is to detect strain



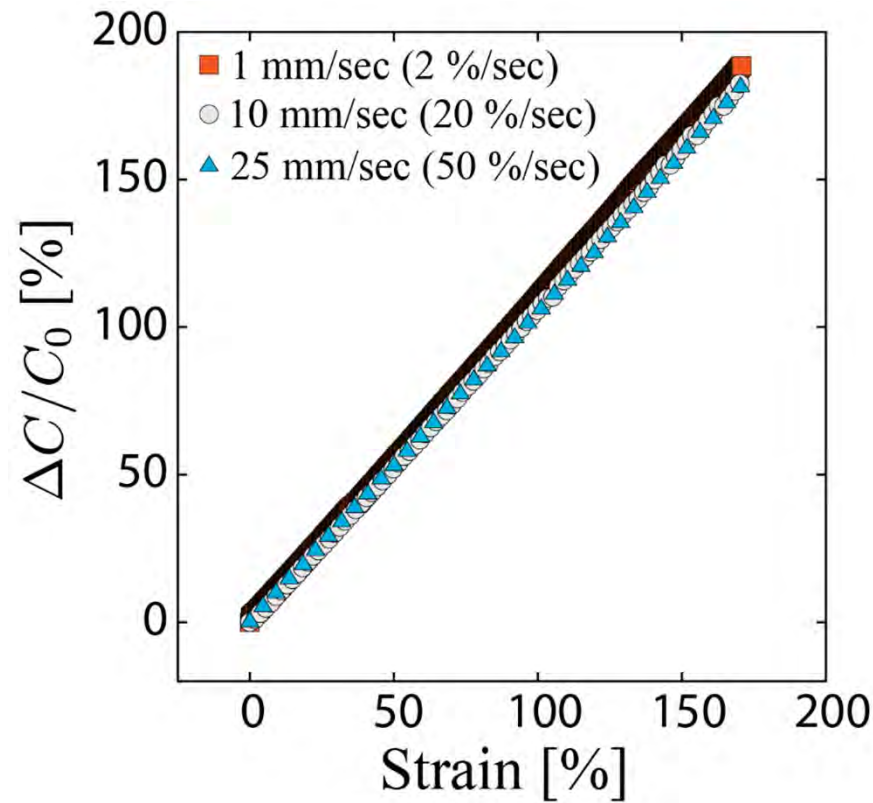
- Capacitive sensing: linear response, low hysteresis, but **low sensitivity**
- Sensitivity, gauge factor (GF):
Ratio of relative change in sensor response to the strain
In capacitive strain sensors, sensitivity is theoretically **limited to 1**

Capacitive sensing showed high linearity and low hysteresis. Resistive sensing had higher sensitivity.

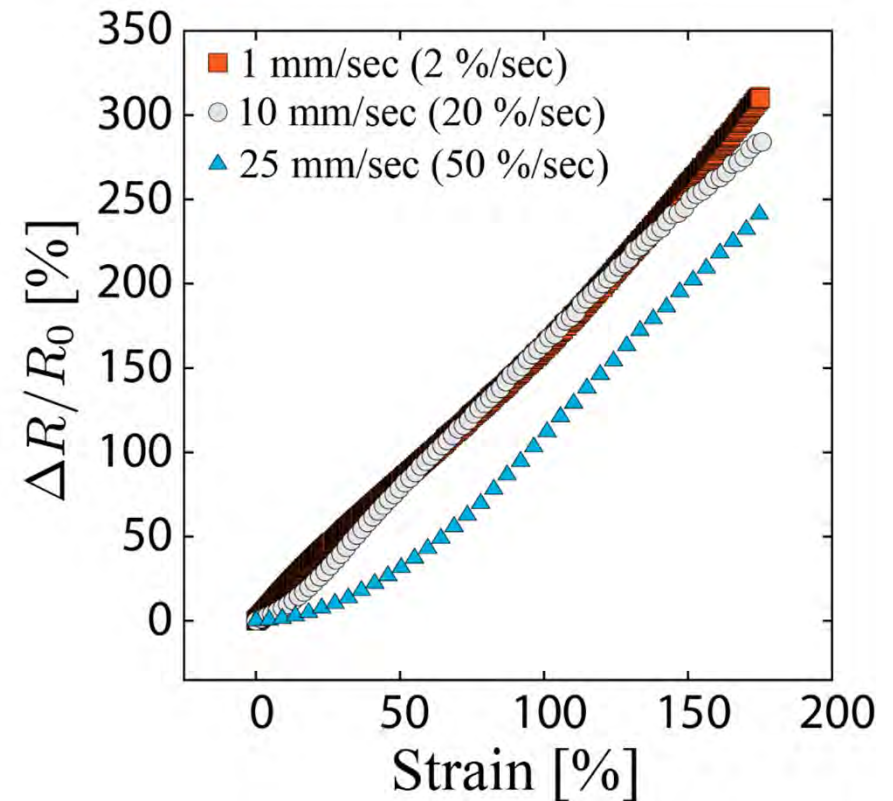
Tested cycle strain: 50, 100, 200, 300, 400, 500 %



Capacitive sensing was more stable for different strain speeds



Capacitive sensing



Resistive sensing

Capacitive sensing mode was more stable also for temperature and multiple cycles.

