Ritsumeikan University
Soft Robotics
November 17/24, 2023
16:20-17:50

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（調布祭）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/

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

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。

研究テーマ

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

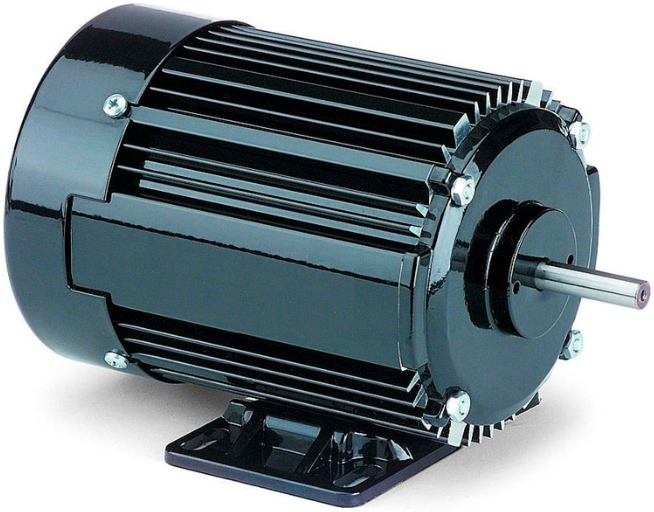
4. 植物ロボティクス

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:

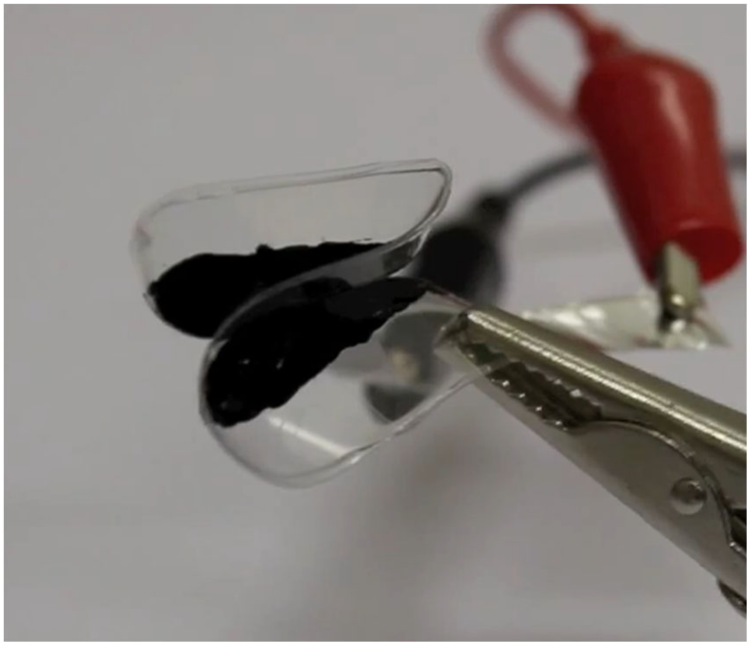


Motor
(directindustry.com)

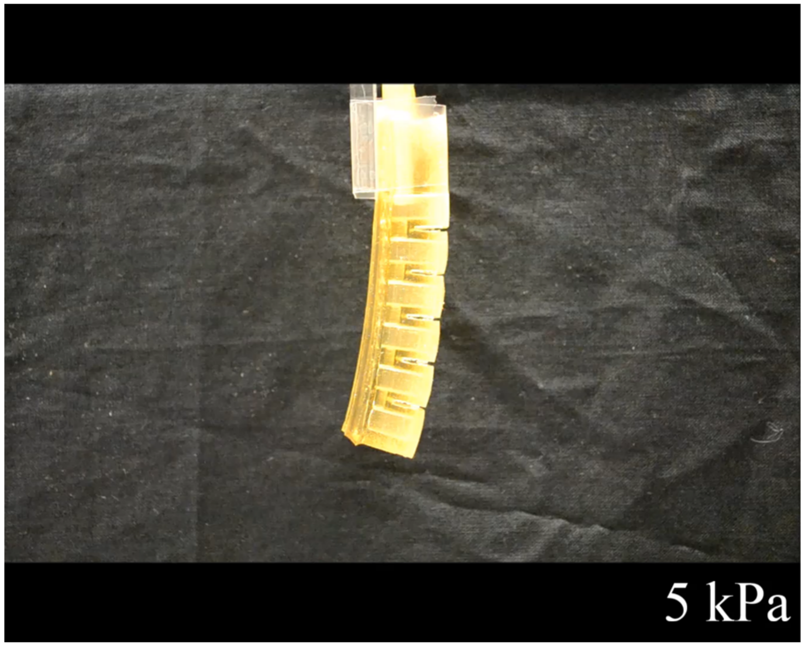
Muscle
(theknowledgepark.blogspot.com)

Soft actuators

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



Electrical soft actuator



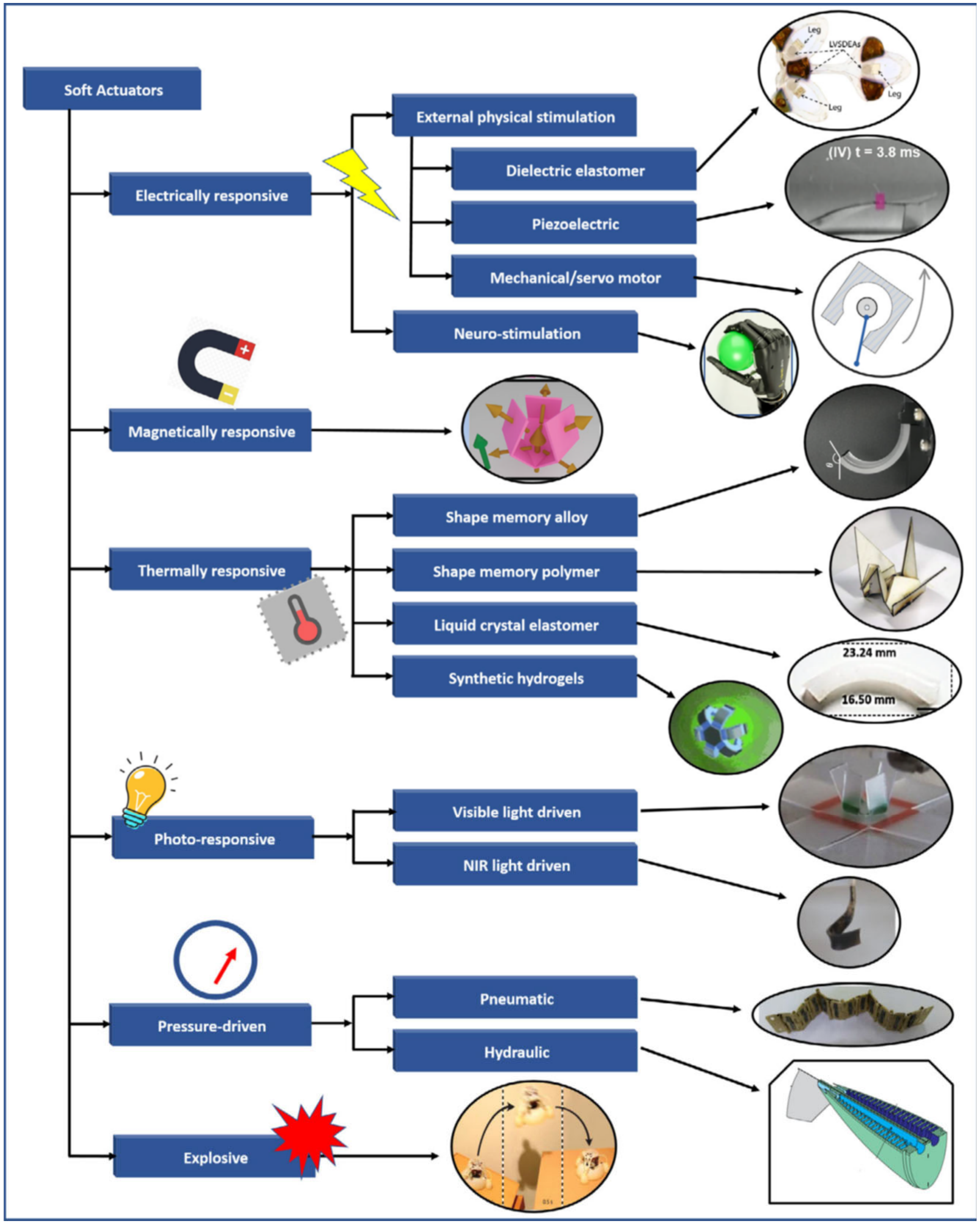
Fluidic soft actuator

Soft actuators

They rely on stimuli of:

- Electric
- Magnetic
- Thermal
- Light
- Pressure

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

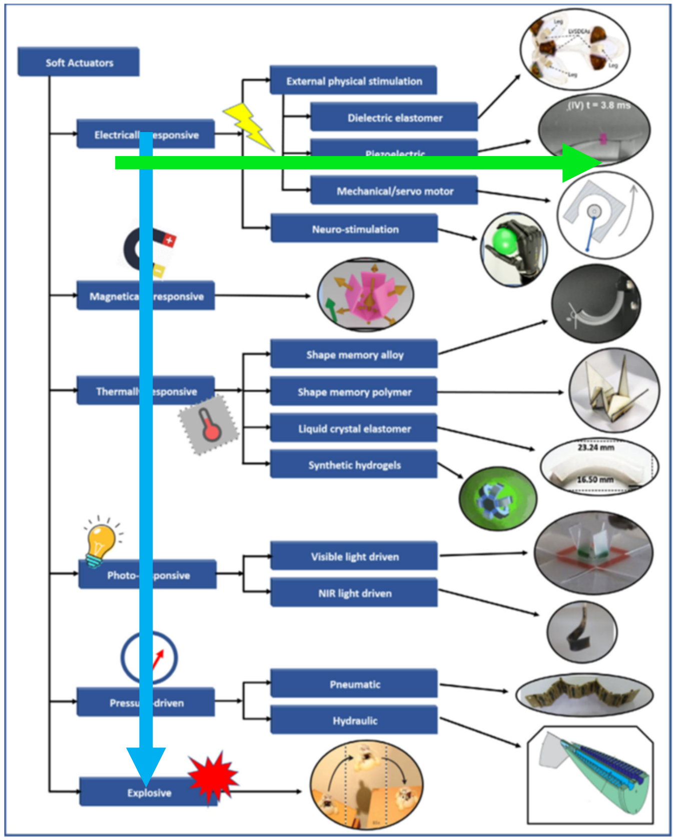


El-Atab, Nazek, et al. "Soft actuators for soft robotic applications: A review." Advanced Intelligent Systems 2.10 (2020): 2000128.

Aim of the topic “Soft Actuators”

11/17: Detail a single soft actuator technology and describe how it enables various actuator configurations and robotic systems.

11/24: Overview existing soft actuators and discuss their pros and cons, followed by homework.

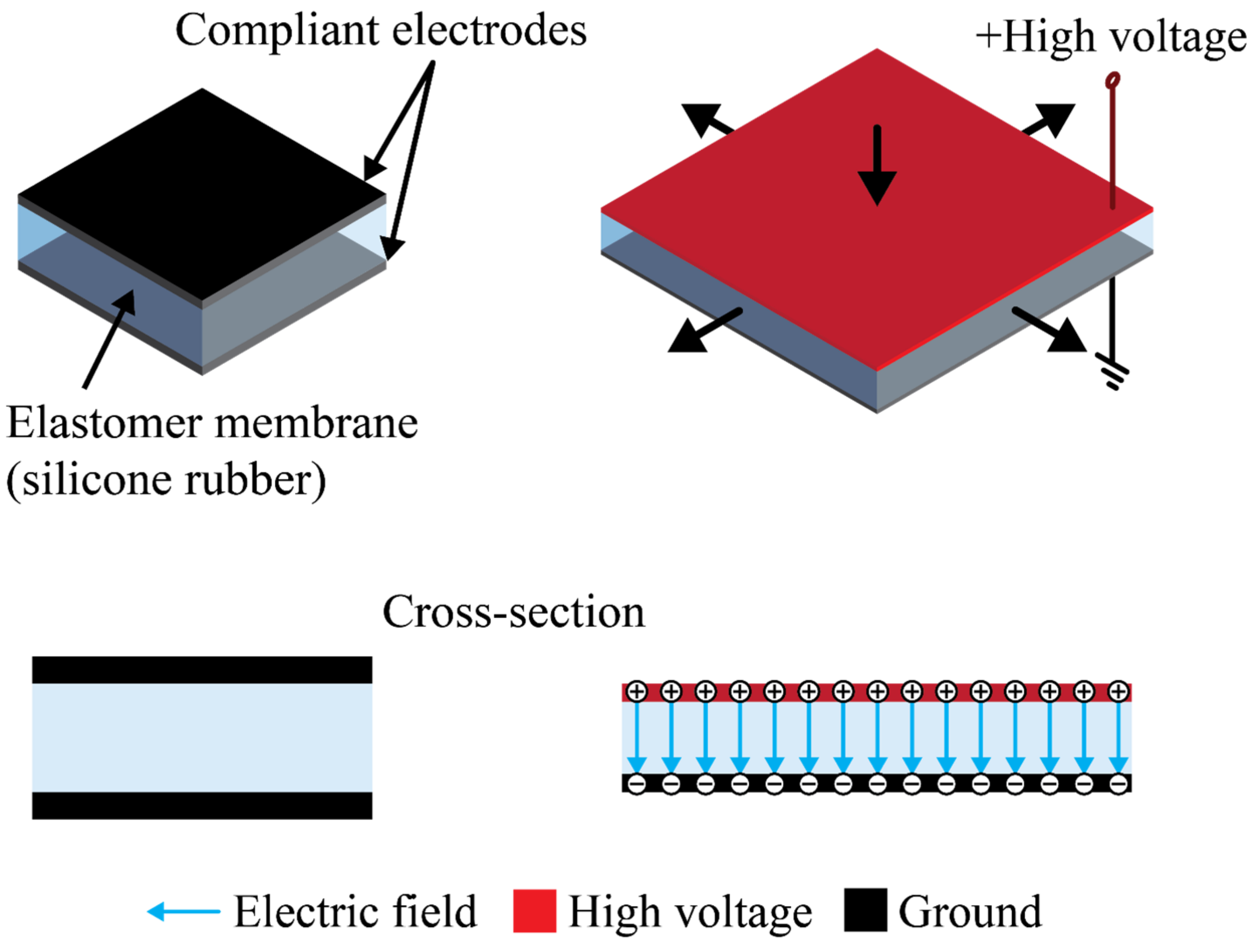


El-Atab, Nazek, et al. "Soft actuators for soft robotic applications: A review." Advanced Intelligent Systems 2.10 (2020): 2000128.

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

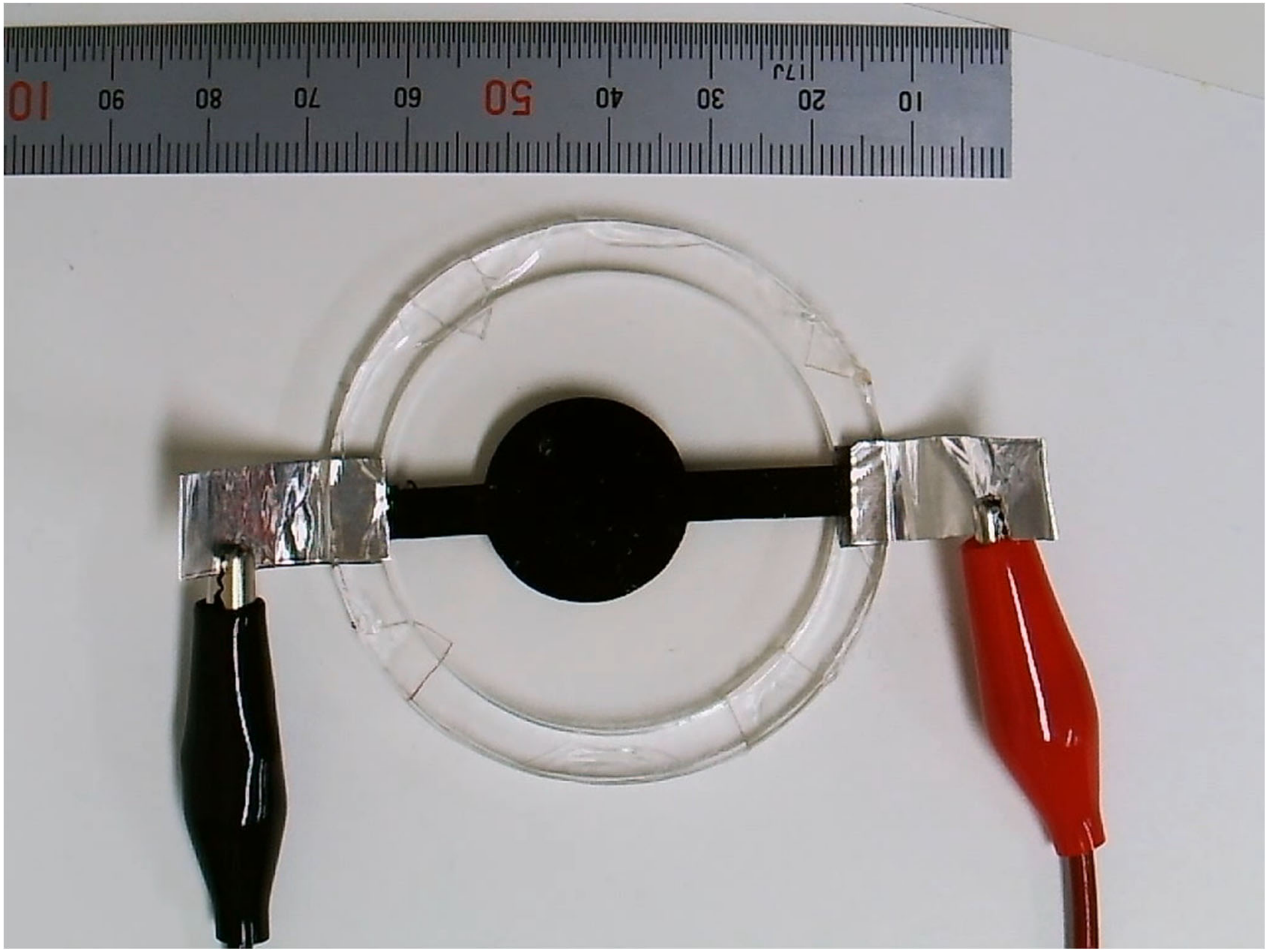
- **Actuator principle and configuration**
- Materials and fabrication methods
- Evaluation methods
- Soft robotic applications

Dielectric elastomer actuators (DEAs)



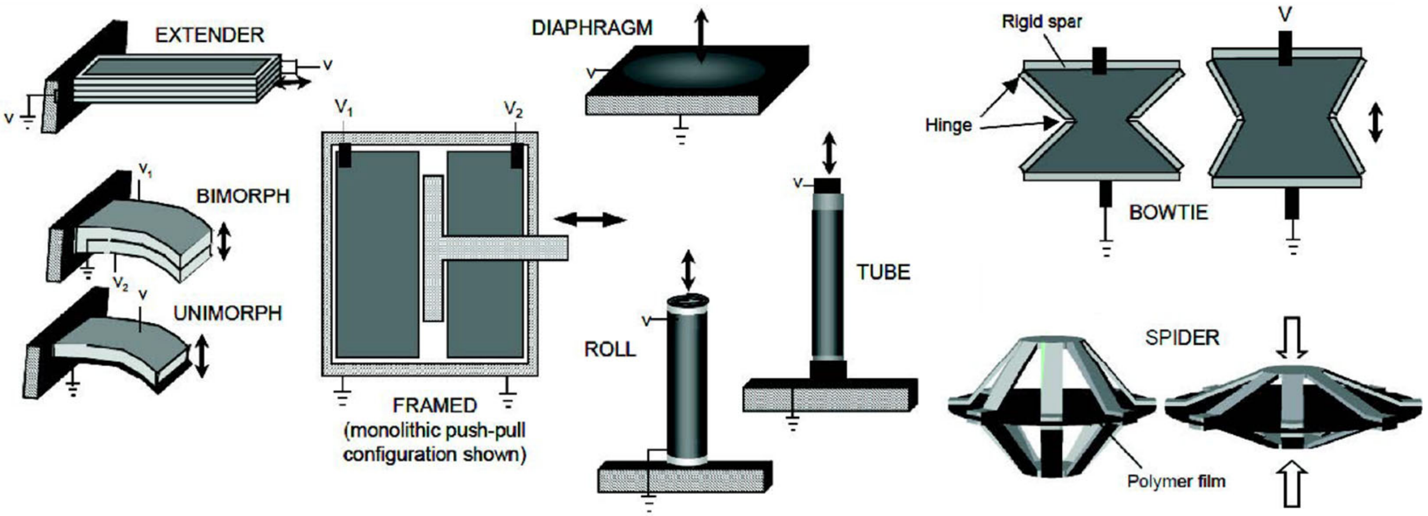
- **Simple**
- **Soft (elastic modulus is ~1 MPa)**
- **Fast (can be actuated at ~1 kHz)**
- **Large actuation strain (~100 % linear stroke)**
- **High voltage (a few kV)**
- **Self-sensing**

DEA in action

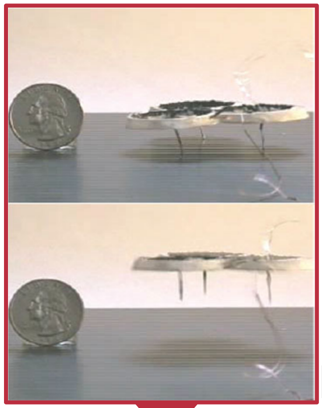


DEAs have been applied to many actuator configurations and robots

[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.



[1]



[2]

[3]

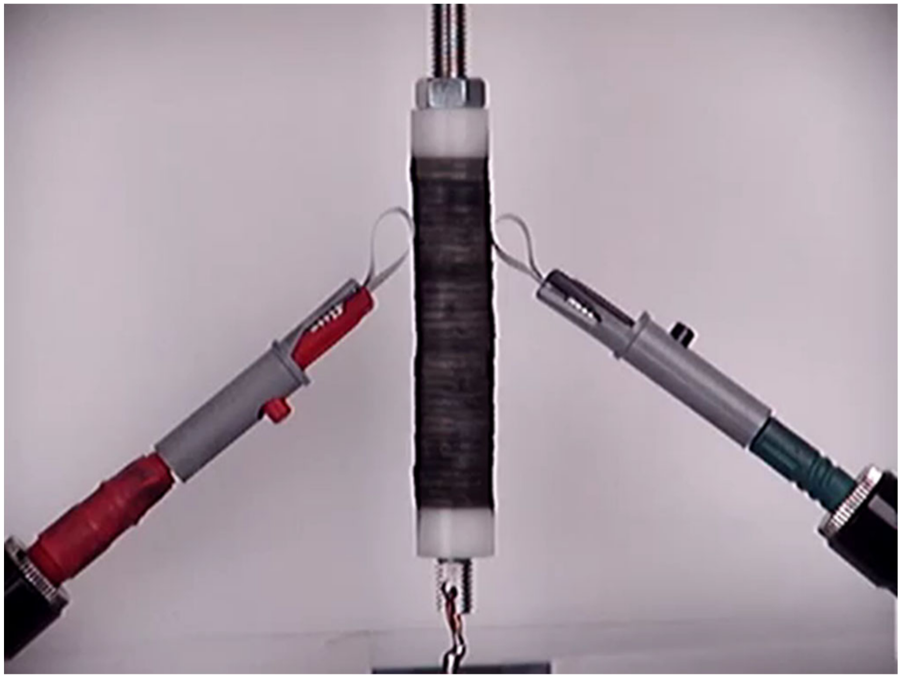
[4]

1cm

10 cm

1 m

Movies:
Stacked DEA and fish-like airship robot

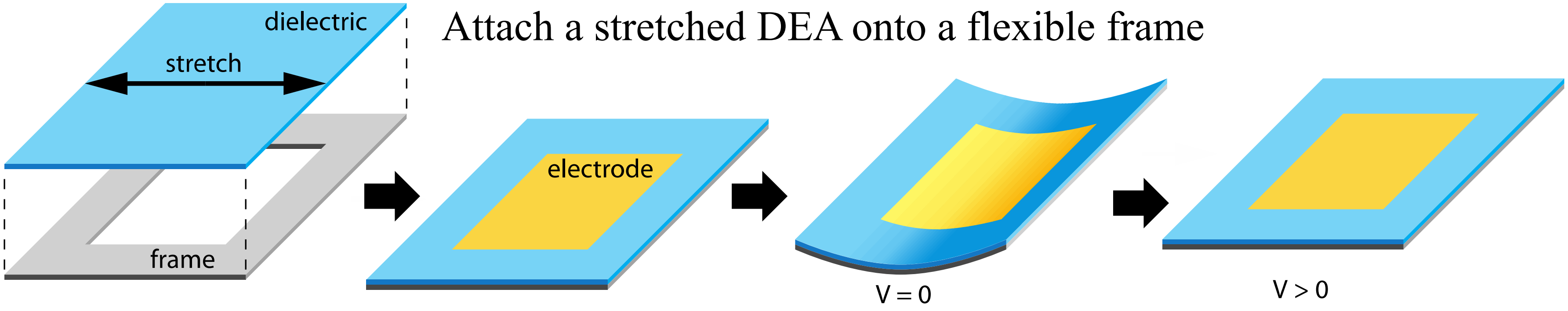


https://www.youtube.com/watch?v=Ga_IafGRWyE

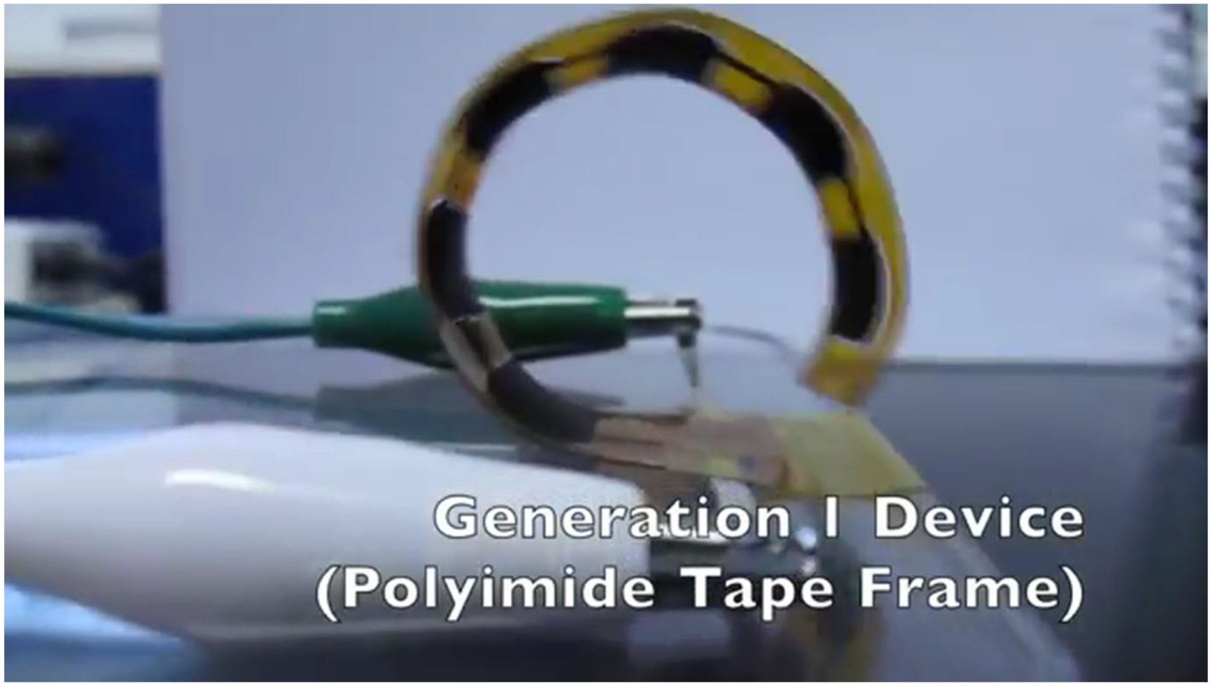
https://www.youtube.com/watch?v=PCmUY1_qAoA

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



Attach a stretched DEA onto a flexible frame

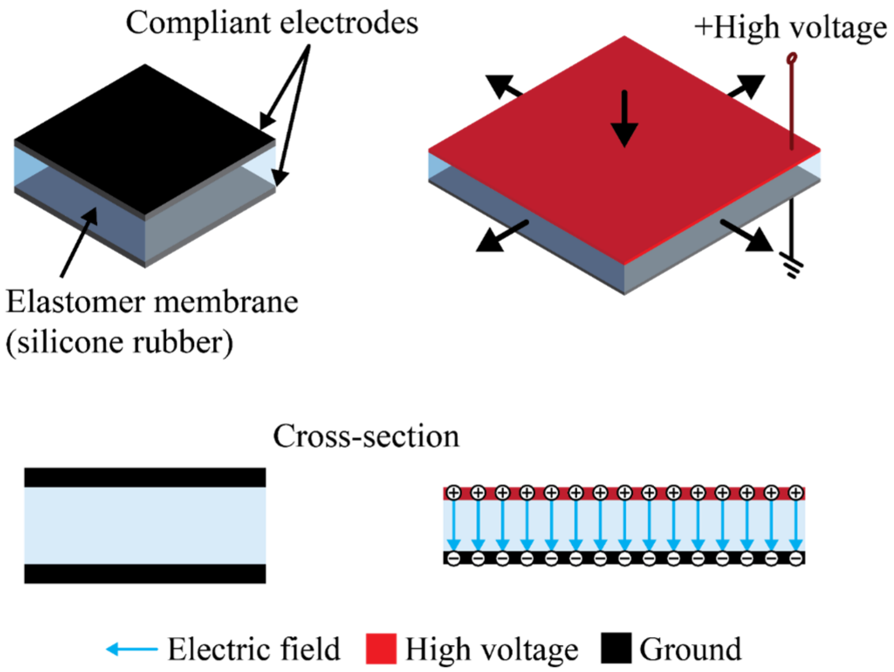


https://www.youtube.com/watch?v=DzX7BHYTTCE

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)



Lager actuation pefromance 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

Permittivity of vacuum

Electric field

Voltage

Electrostatic pressure*

$$p = \varepsilon_0 \varepsilon_r E^2 = \varepsilon_0 \varepsilon_r \left(\frac{V}{d}\right)^2$$

Relative permittivity of membrane

Thickness of membrane

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

$$(s_X+1)\,(s_Y+1)\,(s_z+1) = 1$$

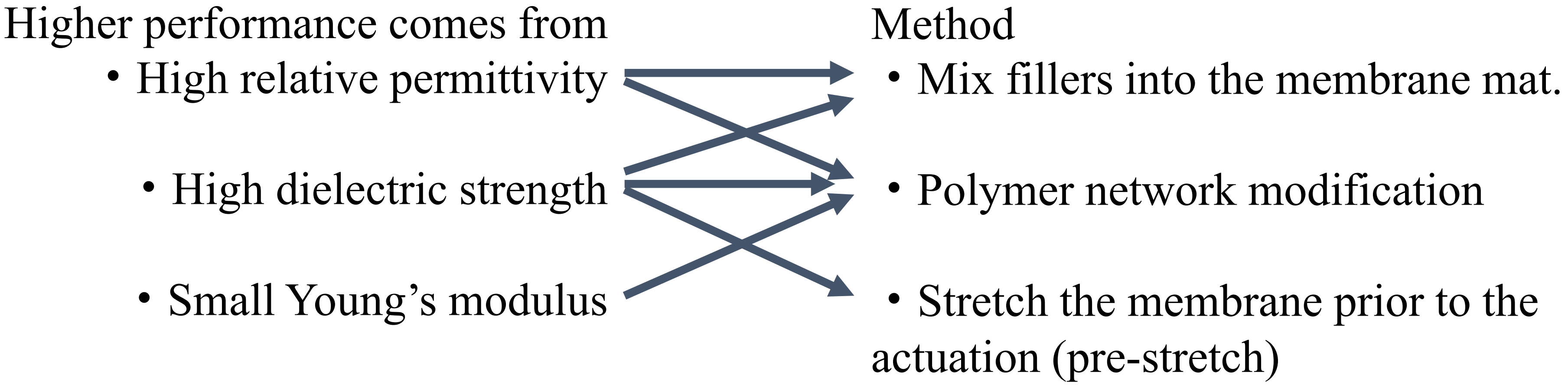
Strain in the thickness direction

$$s_z = \frac{p}{Y}$$

Young’s modulus of membrane

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

Representative ways to improve the actuation performance of DEAs

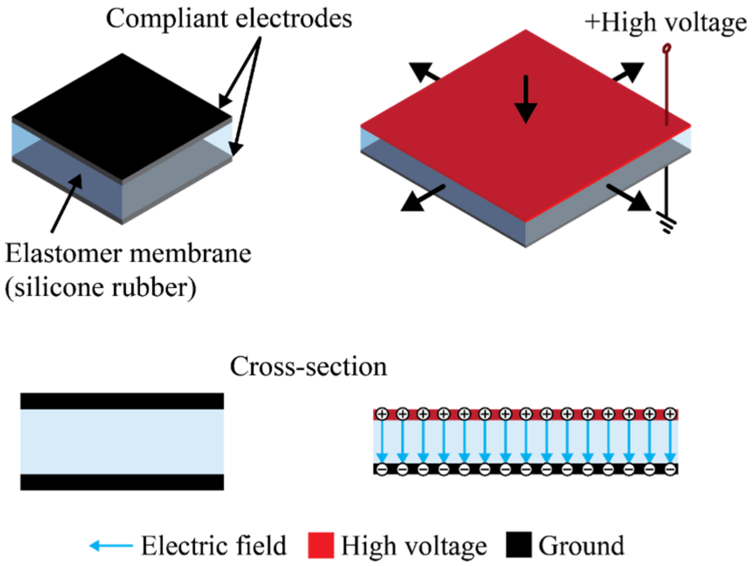


Higher performance comes from

- 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)

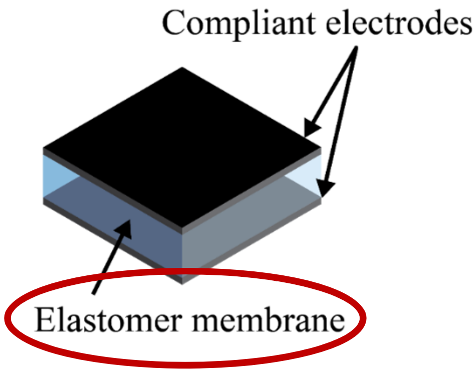


However, there are trade-offs. For instance, even if the relative permittivity increases, the dielectric strength decreases.

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



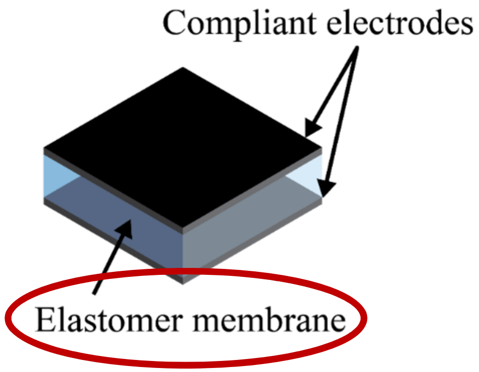
Acrylic and silicone type materials are the two mainstreams.

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

Brochu P, Pei Q. Advances in dielectric elastomers for actuators and artificial muscles. Macromol Rapid Commun. 2010 Jan 4;31(1):10-36. doi: 10.1002/marc.200900425. Epub 2009 Oct 27. PMID: 21590834.

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

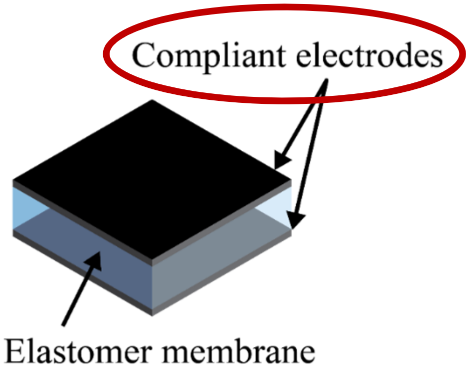
- Nanoparticles (left)

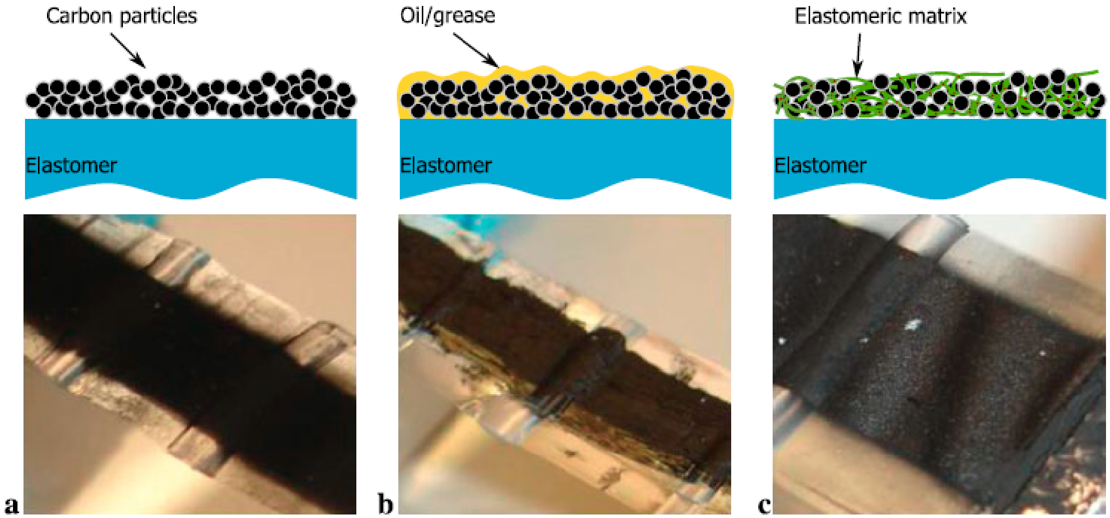
  Carbon black, carbon nanotubes, graphene, silver nanowires, silver, gold, titanium, etc.

- Liquid metal, ionized gel, grease (center)

  Gallium-indium alloy, NaCl-containing gel

- Conductive membrane (mixing conductive particles) (right)

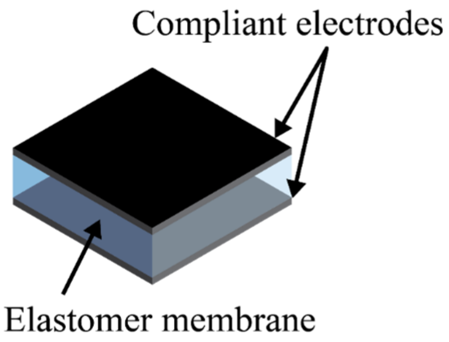




Rosset, Samuel, and Herbert R. Shea. "Flexible and stretchable electrodes for dielectric elastomer actuators." *Applied Physics A* 110.2 (2013): 281-307.

- 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.

Method to fabricate membranes and pattern electrodes



Membrane

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

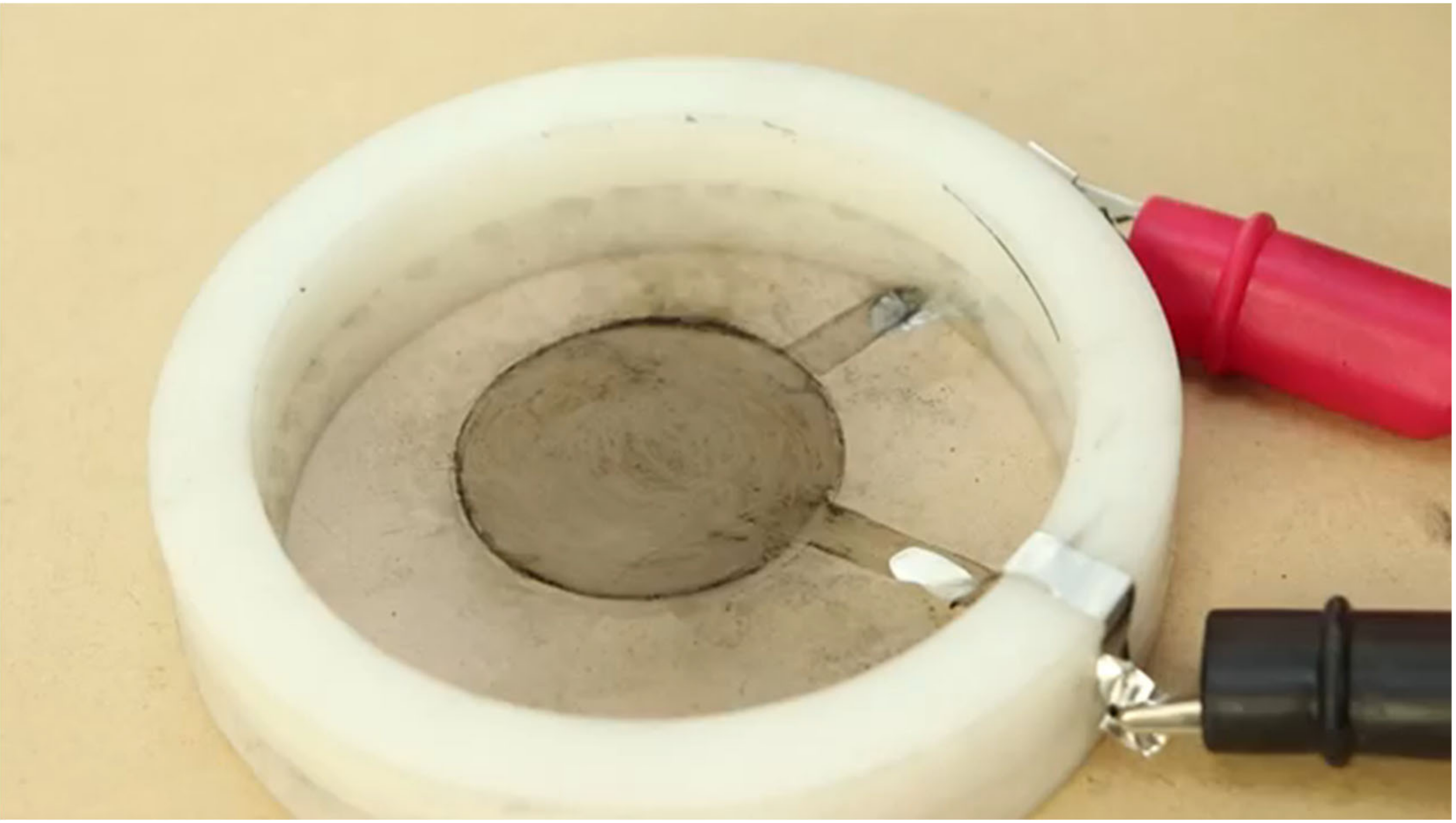
Electrode

- 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

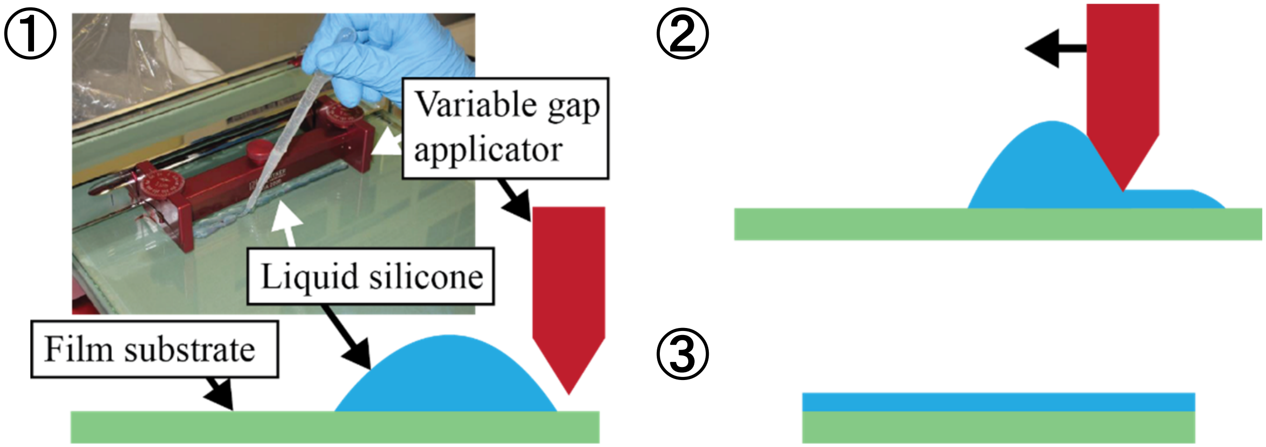
Film applicator

Zehntner, ZAA2300

Gap applicator

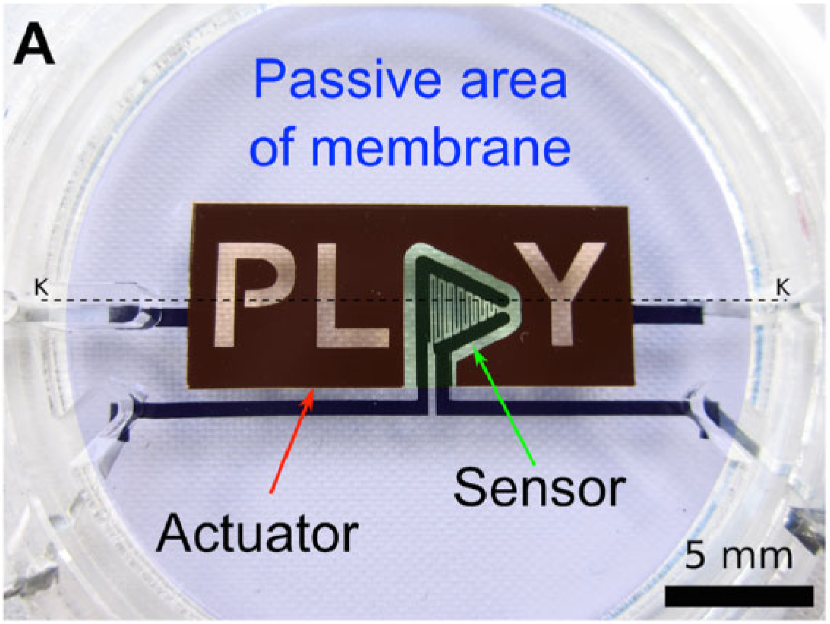
Zehntner, ZUA2000

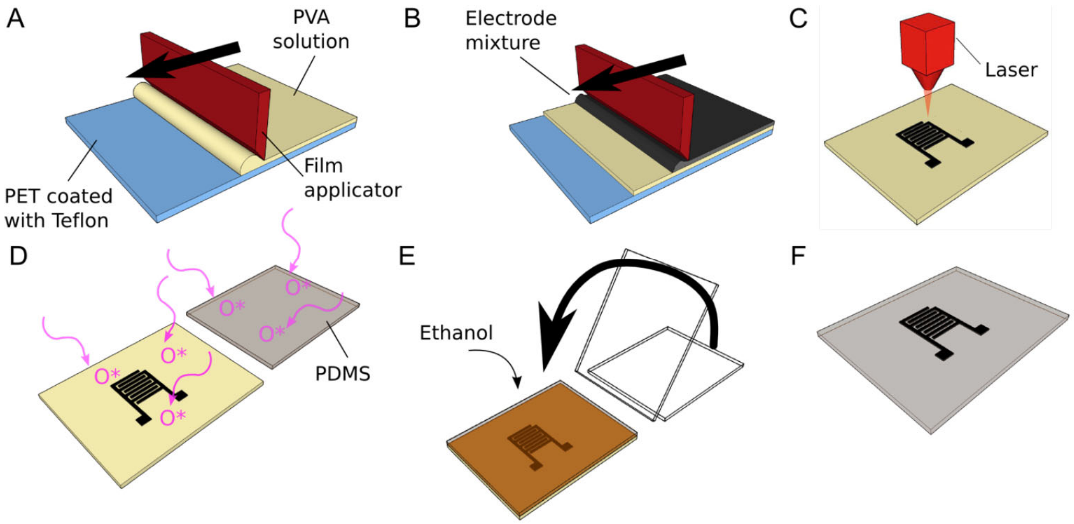
- Desired membrane thickness can be obtained.
- Large area (~20 cm × 30 cm)
- Conductive membrane can also be fabricated.



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.

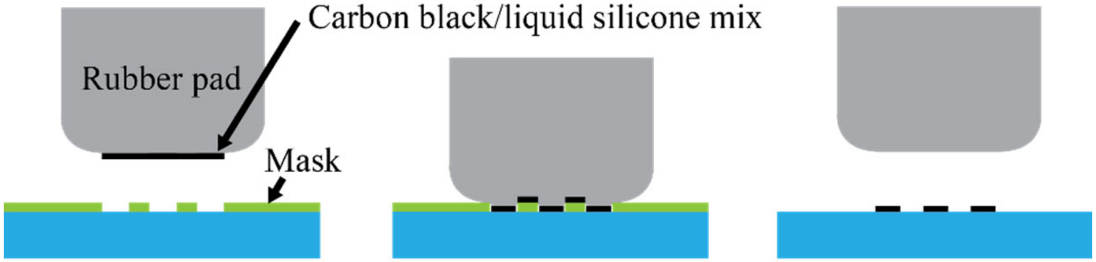
*Araromi, Oluwaseun A., Samuel Rosset, and Herbert R. Shea. "High-resolution, large-area fabrication of compliant electrodes via laser ablation for robust, stretchable dielectric elastomer actuators and sensors." *ACS applied materials & interfaces* 7.32 (2015): 18046-18053.

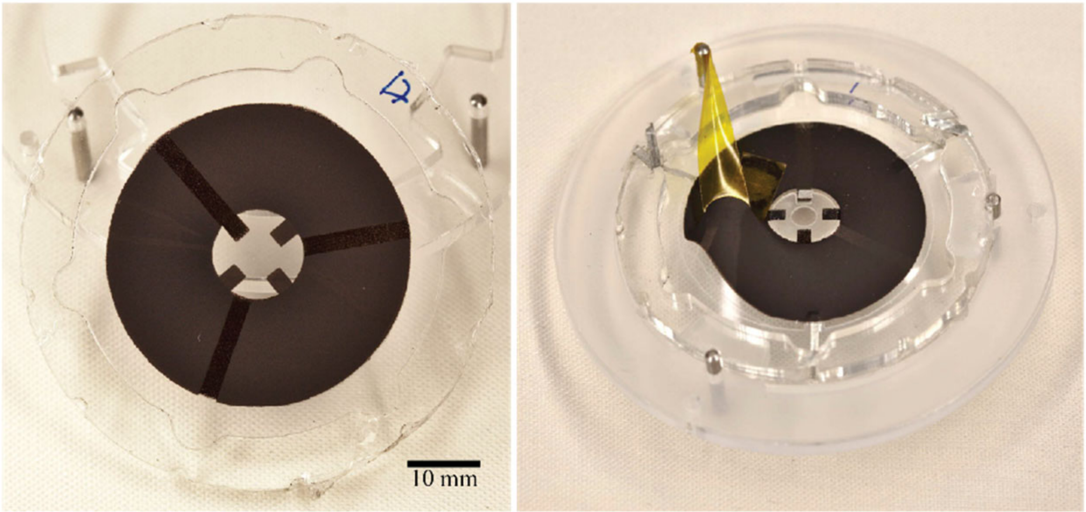
Pad printing

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

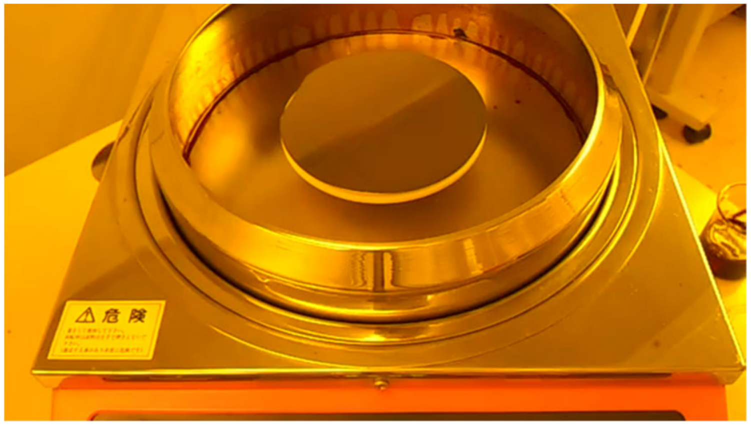




- Thin electrodes can be easily formed (thickness 1-5 um)
- Electrode area is about Φ100 mm
- Non conductive membrane can also be produced, but with lower precision in thickness

Spin coating

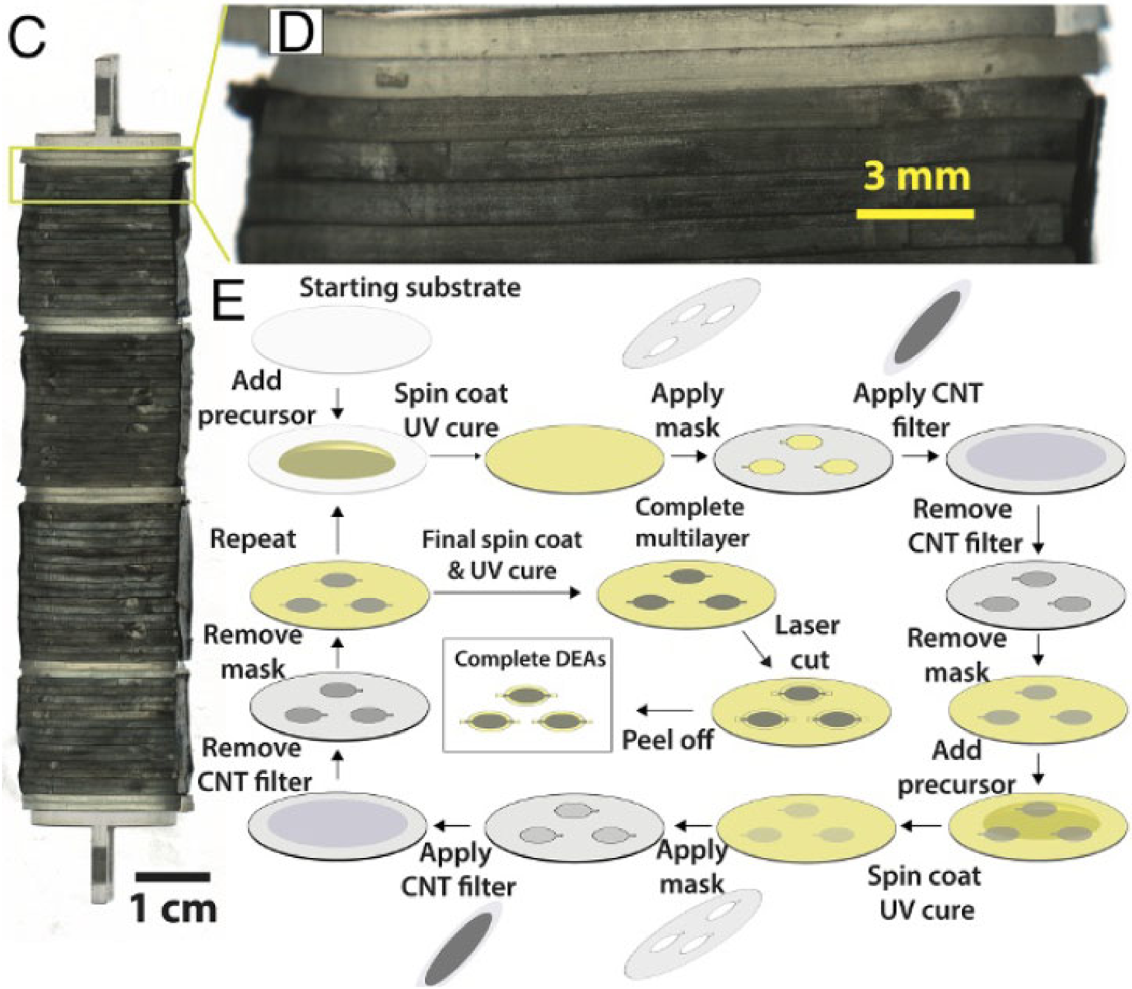
Spin coater



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



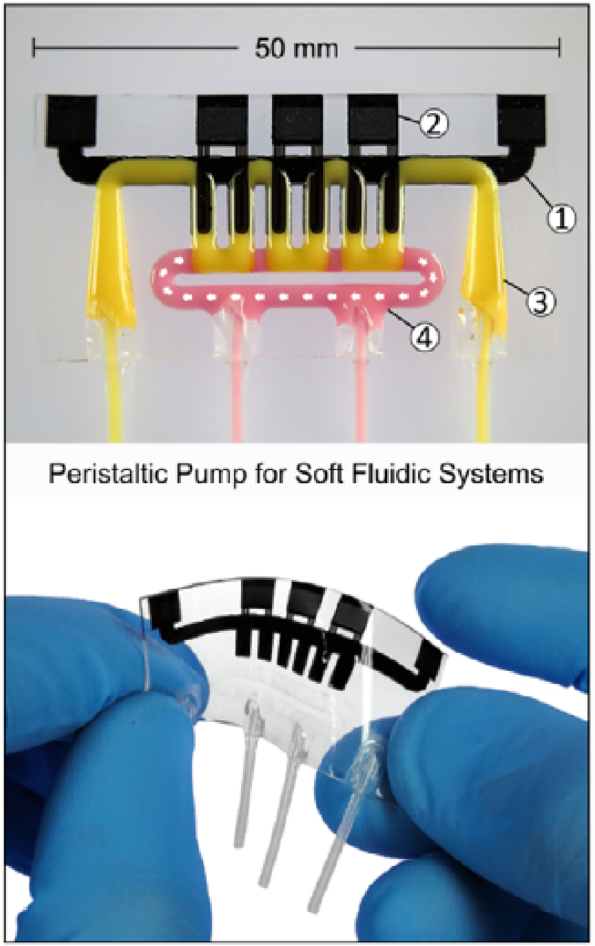
Duduta, Mihai, et al. "Realizing the potential of dielectric elastomer artificial muscles." *Proceedings of the National Academy of Sciences* 116.7 (2019): 2476-2481.

Ink jet (incl. 3D printing)

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

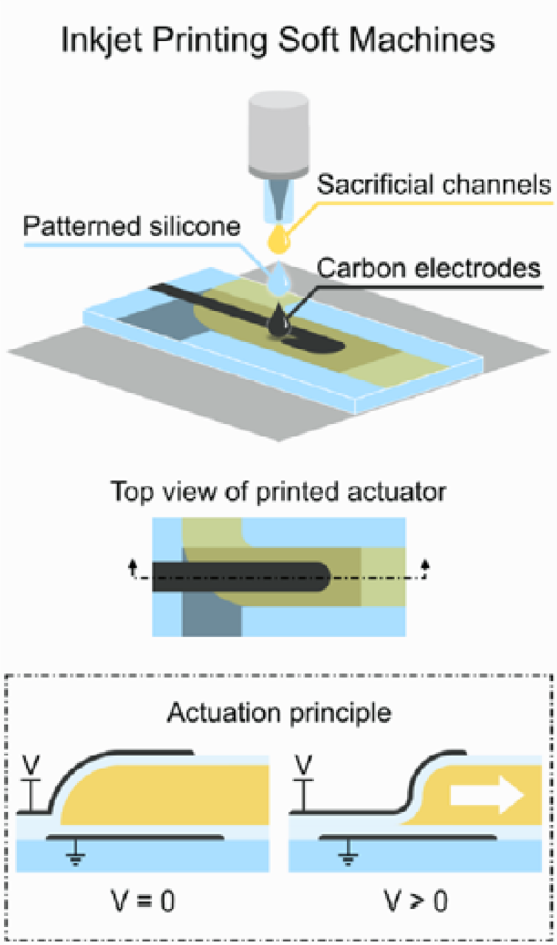
- Can be produced DEAs in various shapes with high precision, but the preparation of inks is often difficult and the equipment is complex.

(a)



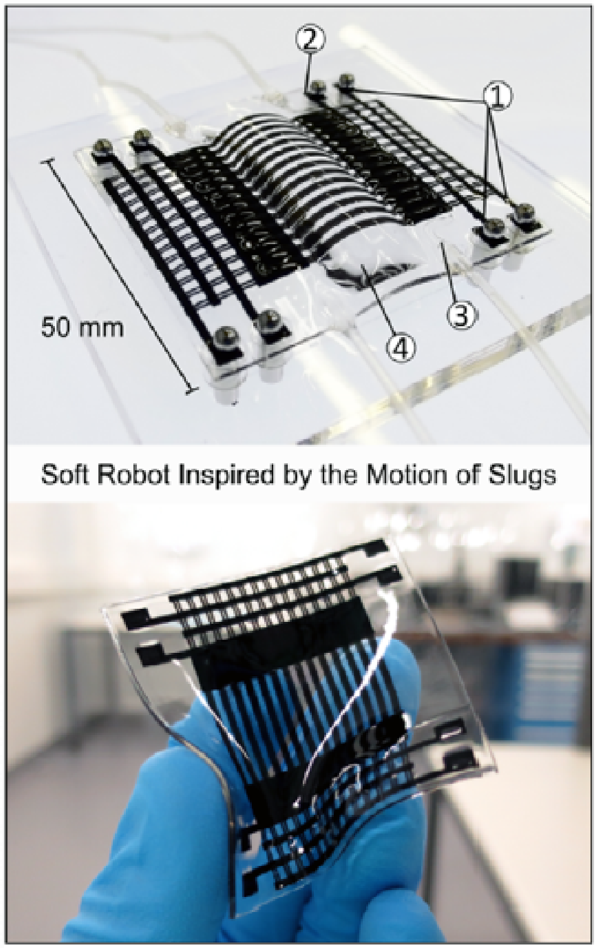
Peristaltic Pump for Soft Fluidic Systems

(b)



Inkjet Printing Soft Machines

(c)



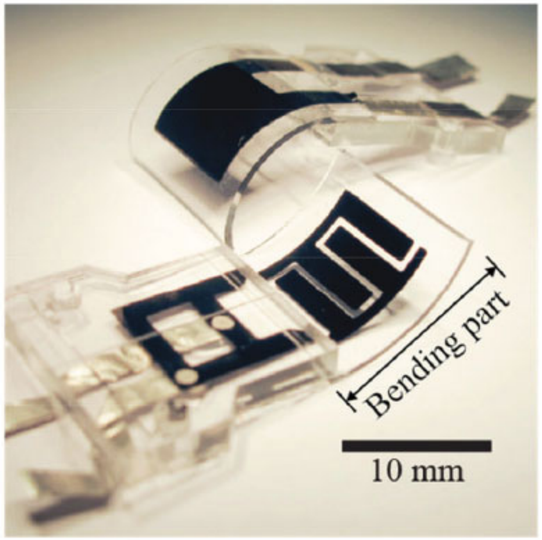
Soft Robot Inspired by the Motion of Slugs

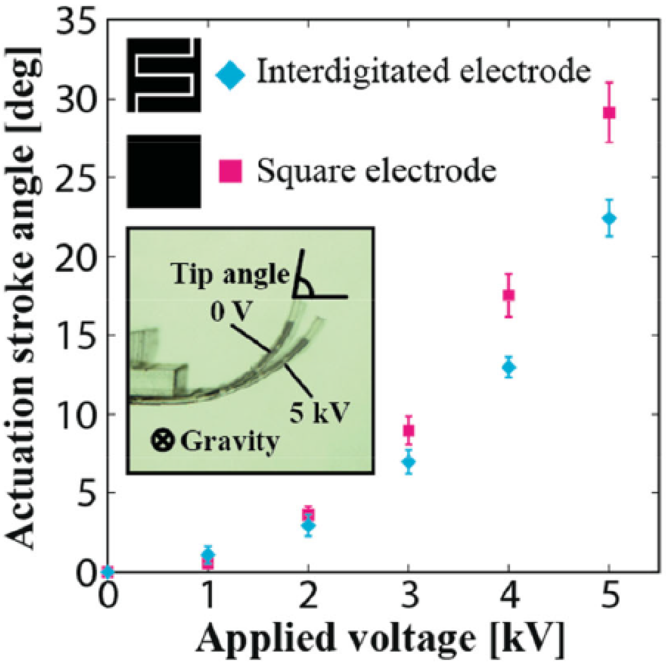
Detail a single soft actuator technology: Dielectric elastomer actuators (DEAs)

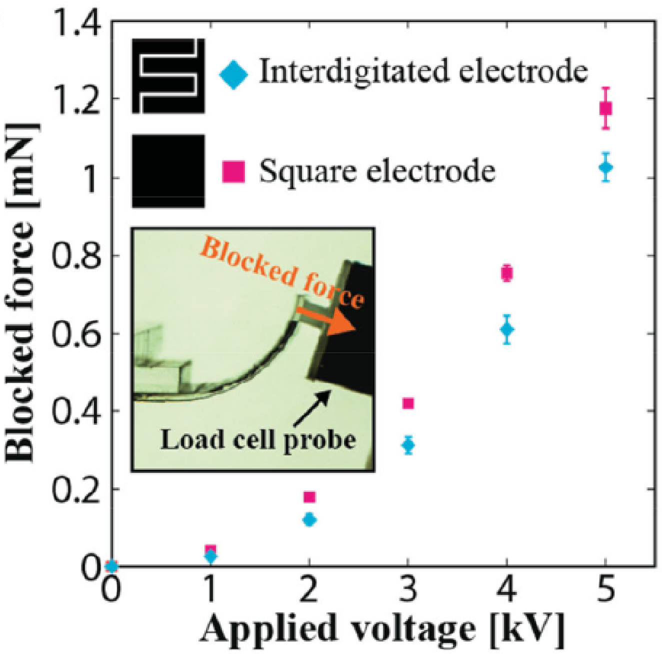
- Actuator principle and configuration
- Materials and fabrication methods
- **Evaluation methods**
- Soft robotic applications

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

Shintake, Jun, et al. "Versatile soft grippers with intrinsic electroadhesion based on multifunctional polymer actuators." *Advanced Materials* 28.2 (2016): 231-238.

Equipment to drive DEAs;
High-voltage power supplies

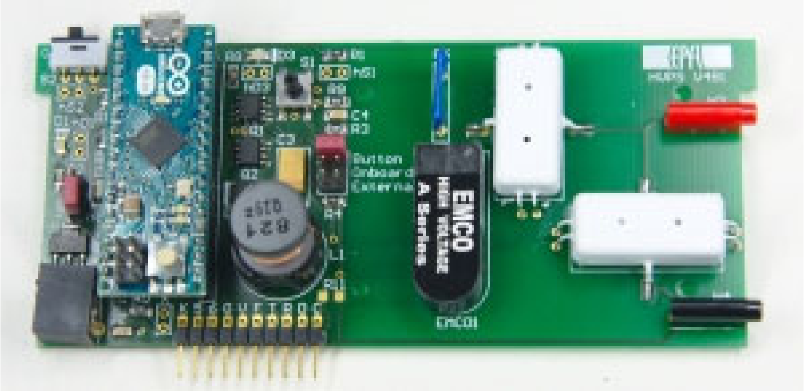
- DC/DC converter (Direct use)

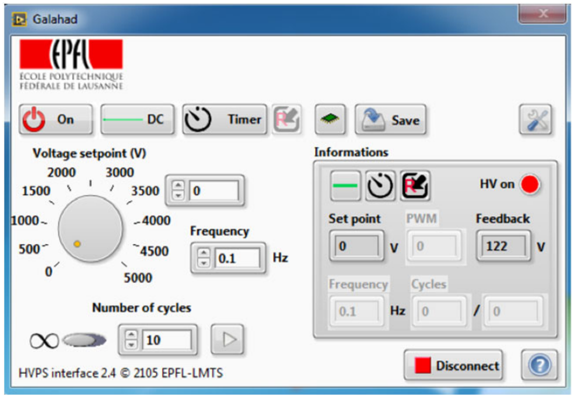
Example: XP Power CB101N (10 kV)

- Commercially available high-voltage power supply

Example: Matsusada HEOP-5B6 (5 kV)

- Open source high voltage power supply (5 kV)





Voltage setpoint (V) 0

Frequency 0.1 Hz

Number of cycles 10

Set point 0 V

PWM 0

Feedback 122 V

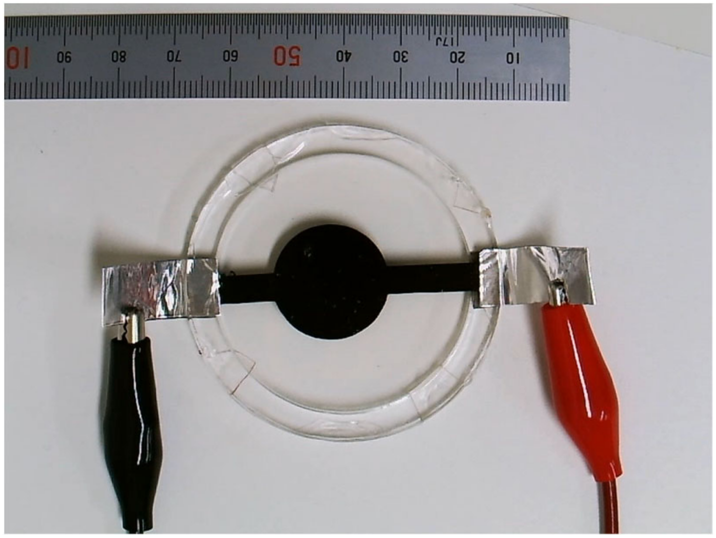
Frequency 0.1 Hz

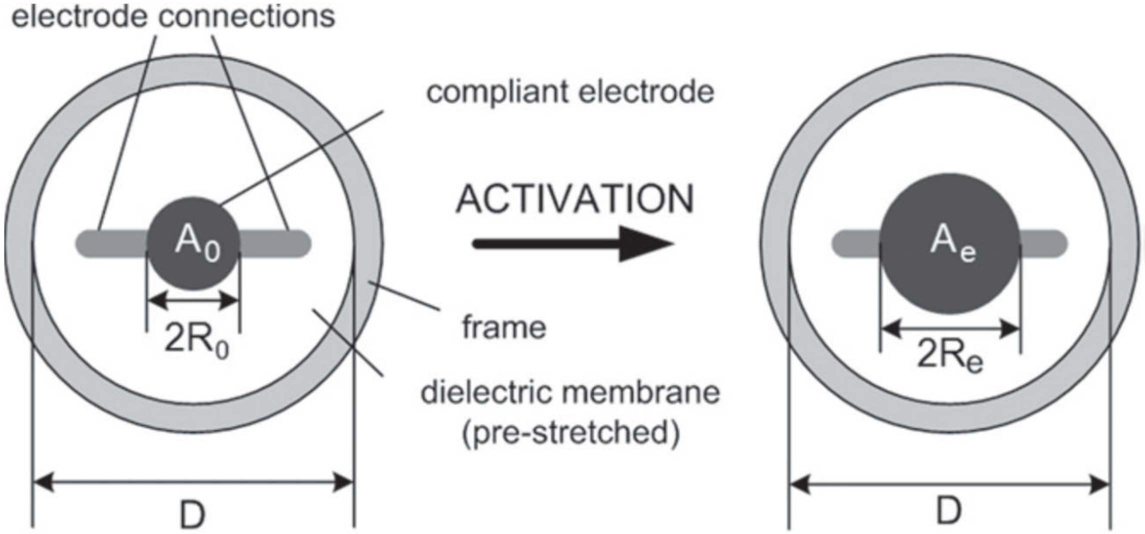
Cycles 0 / 0

HVPS interface 2.4 © 2105 EPFL-LMTS

https://petapicovoltron.com/high-voltage-power-supplies/single-channel-high-voltage-power-supply/

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 2R0
- Membrane should be pre-stretched

Strain in the thickness direction

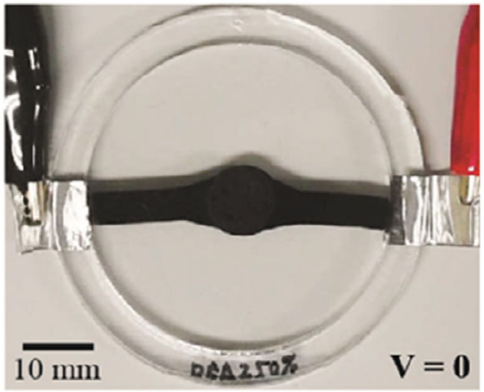
$$S_{e,z} = \frac{1}{\left(S_{e,r} + 1\right)^2} - 1$$

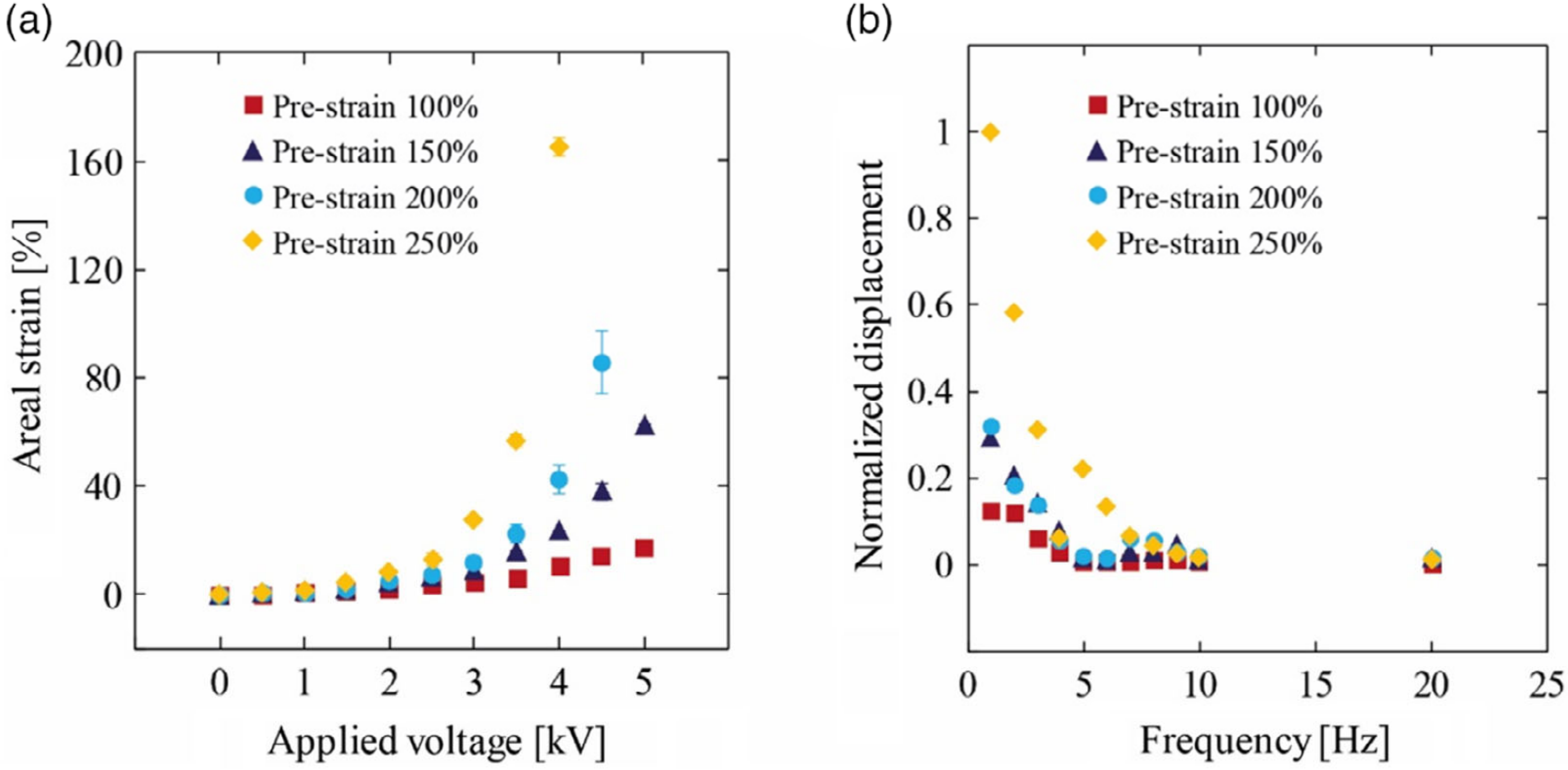
Strain in the radial direction

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

Standard evaluation sample: Circular DEAs

Example of measured result

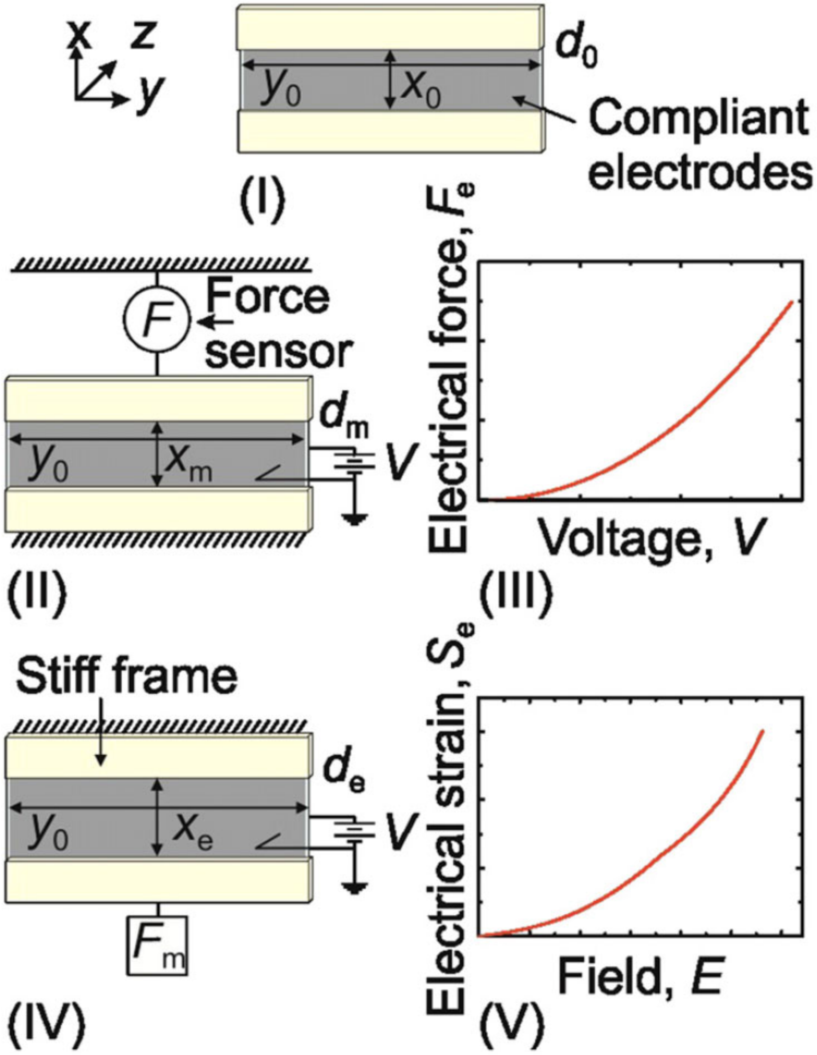




Kanno, Ryo, Toshiaki Nagai, and Jun Shintake. "Rapid Fabrication Method for Soft Devices Using Off-the-Shelf Conductive and Dielectric Acrylic Elastomers." *Advanced Intelligent Systems*: 2000173.

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

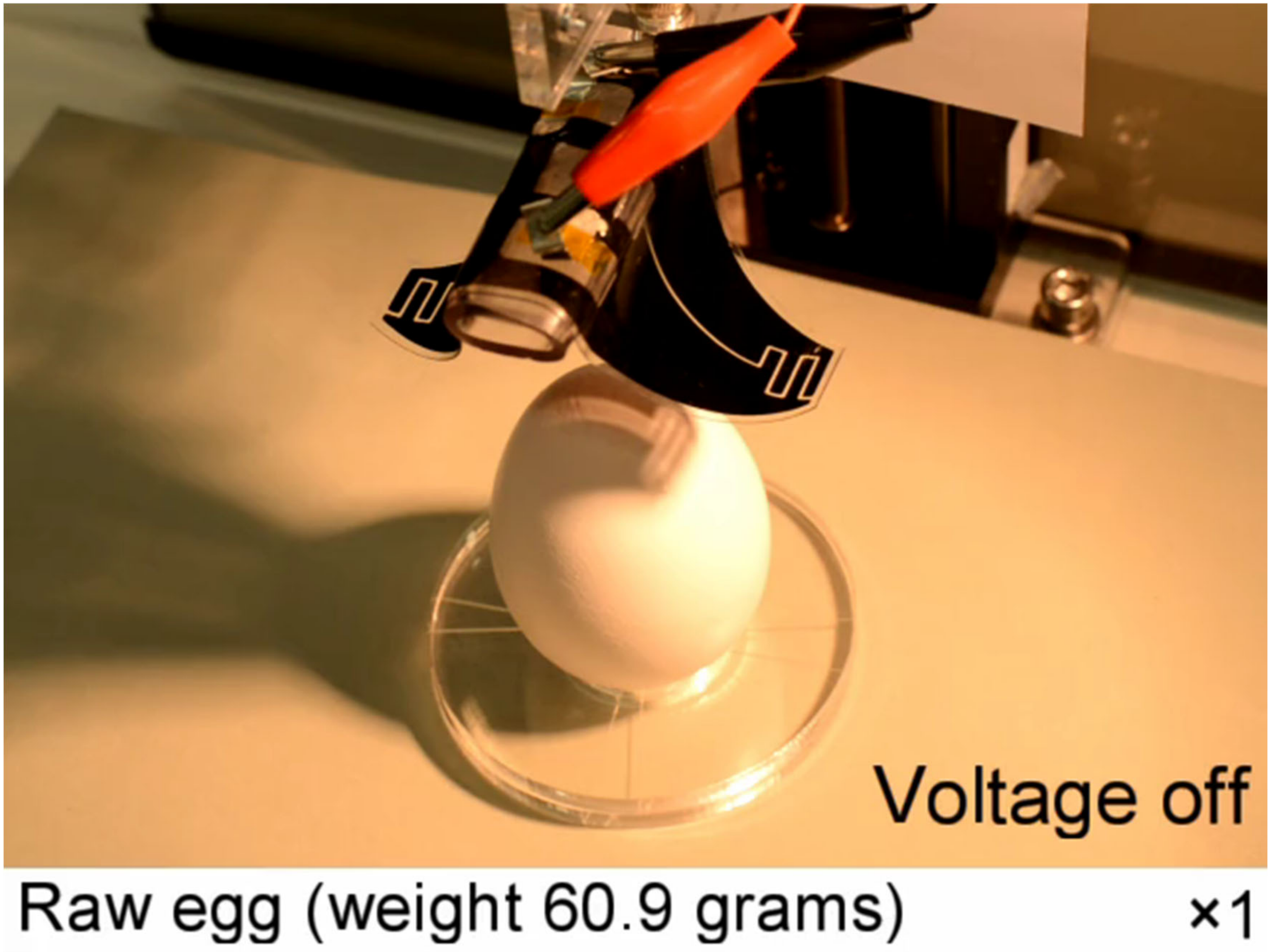


Carpi, Federico, et al. "Standards for dielectric elastomer transducers." *Smart Materials and Structures* 24.10 (2015): 105025.

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

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

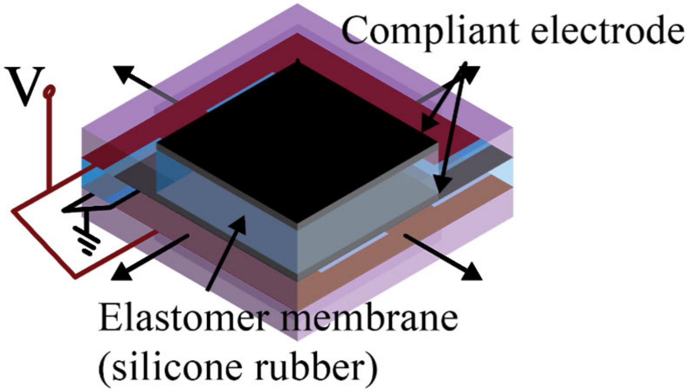
Soft gripper

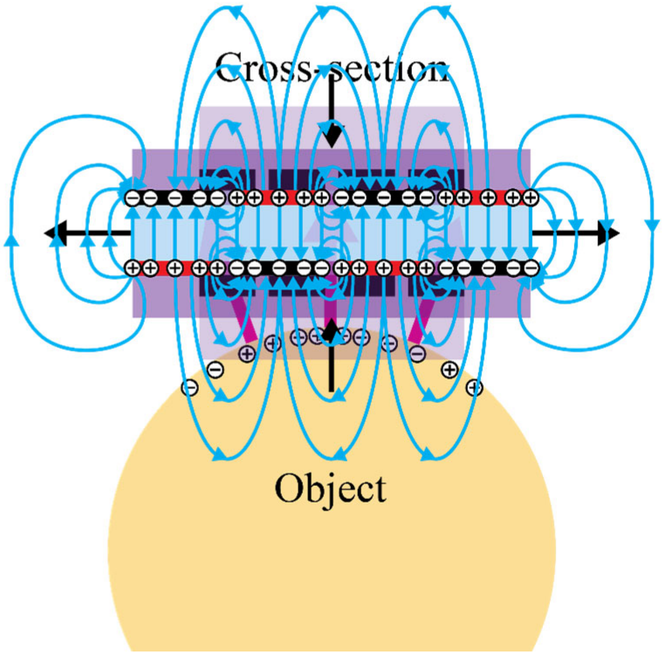


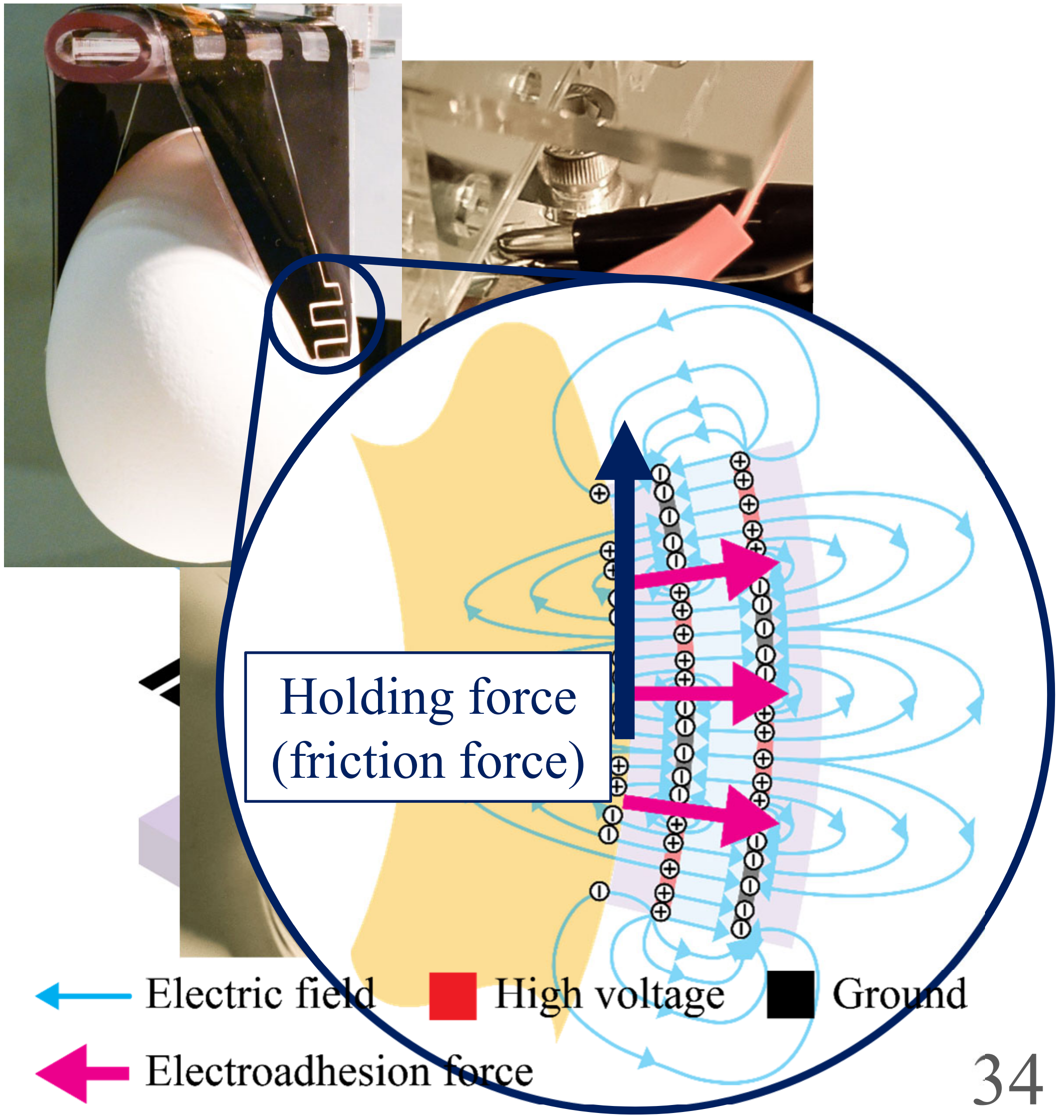
Shintake, Jun, et al. "Versatile soft grippers with intrinsic electroadhesion based on multifunctional polymer actuators." *Advanced Materials* 28.2 (2016): 231-238.

J. Shintake et al., *Adv. Mater.* **2016**, *28*, 231.

Gripper holds objects by electro-adhesion







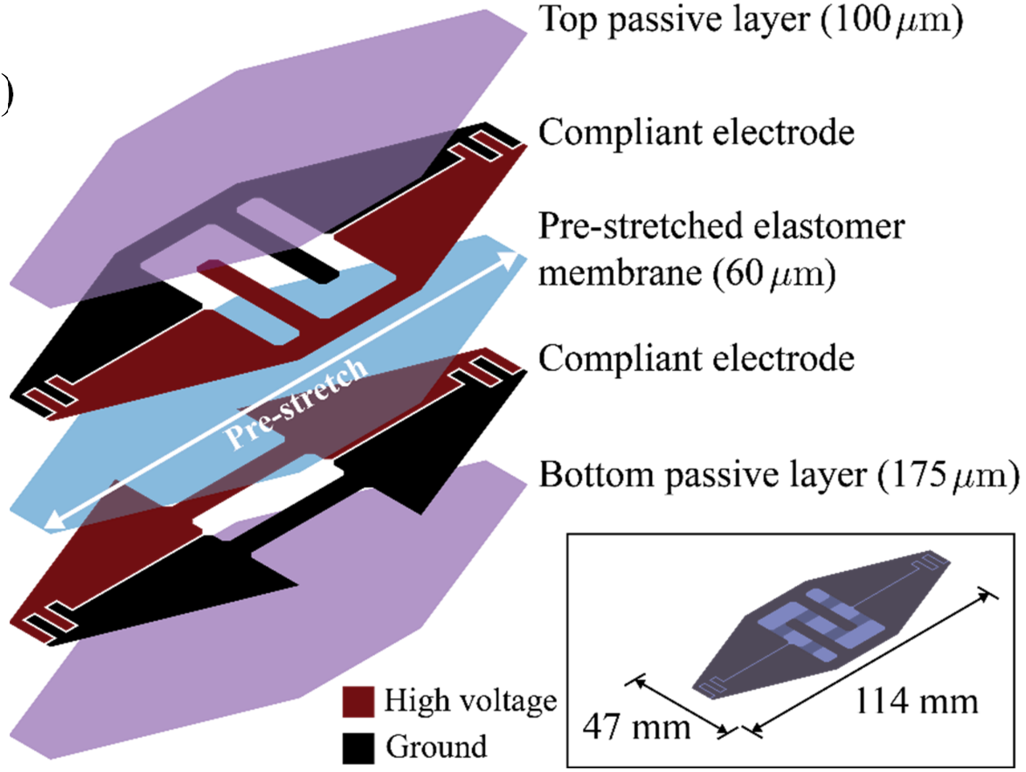
Materials and fabrication method used for the gripper

Materials

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

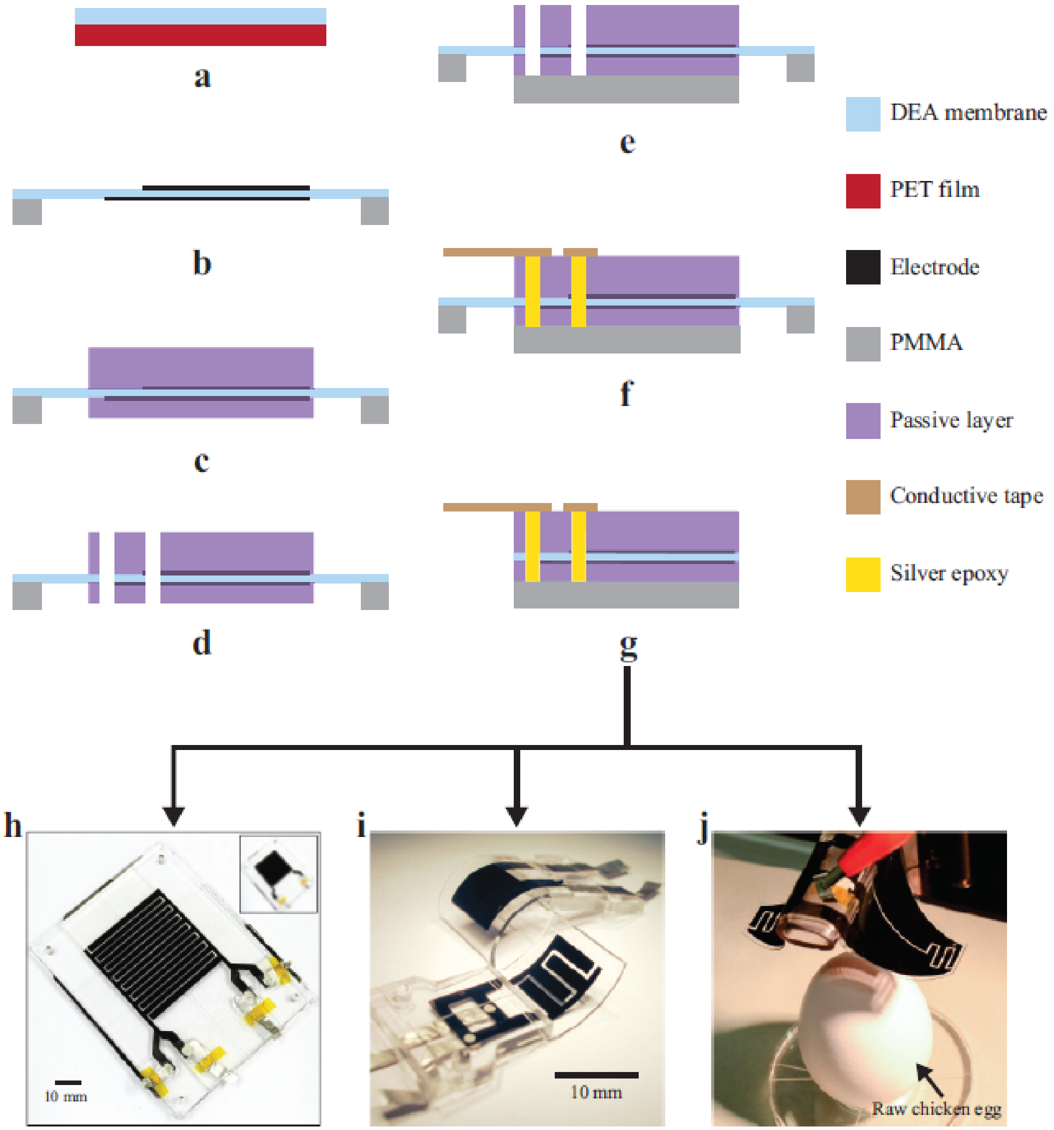
Fabrication method

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



Structural composition of the gripper

Fabrication process used for the gripper



A. CF19-2184 is blade-cast on PET film and cured in an oven at 80 °C (60 um)

B. Cured CF19-2184 is pre-stretched and held, and electrodes are applied by pad printing (3 um). Electrodes are cured in an oven (80 °C)

C. Sylgard 184 membranes (100, 75 um) are made by blade casting and bonded by O2 plasma

D. Make holes in the electrodes to establish connections

E. Place the sample on an acrylic sheet

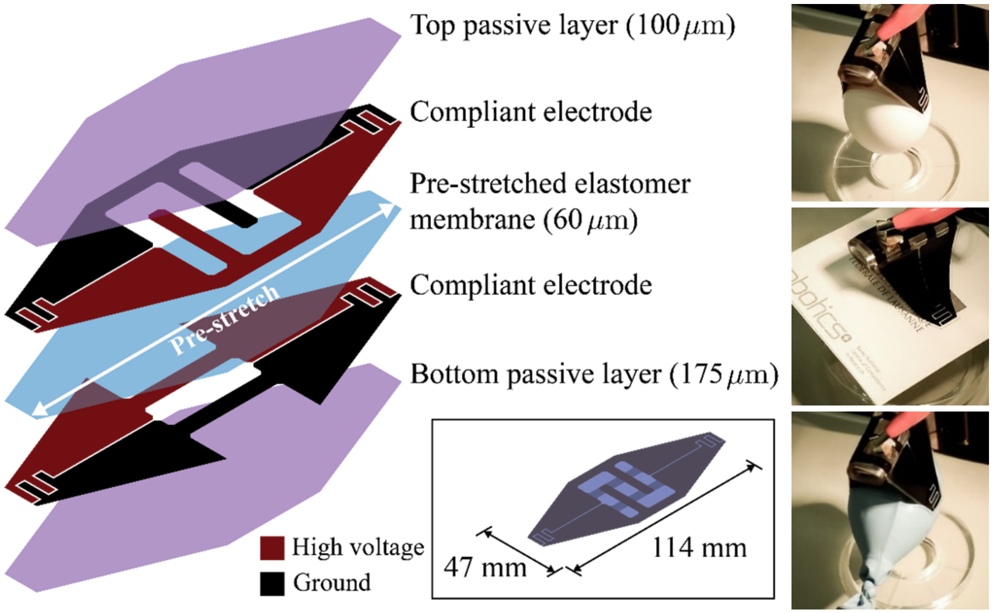
F. Fill the hole with silver epoxy

G. 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

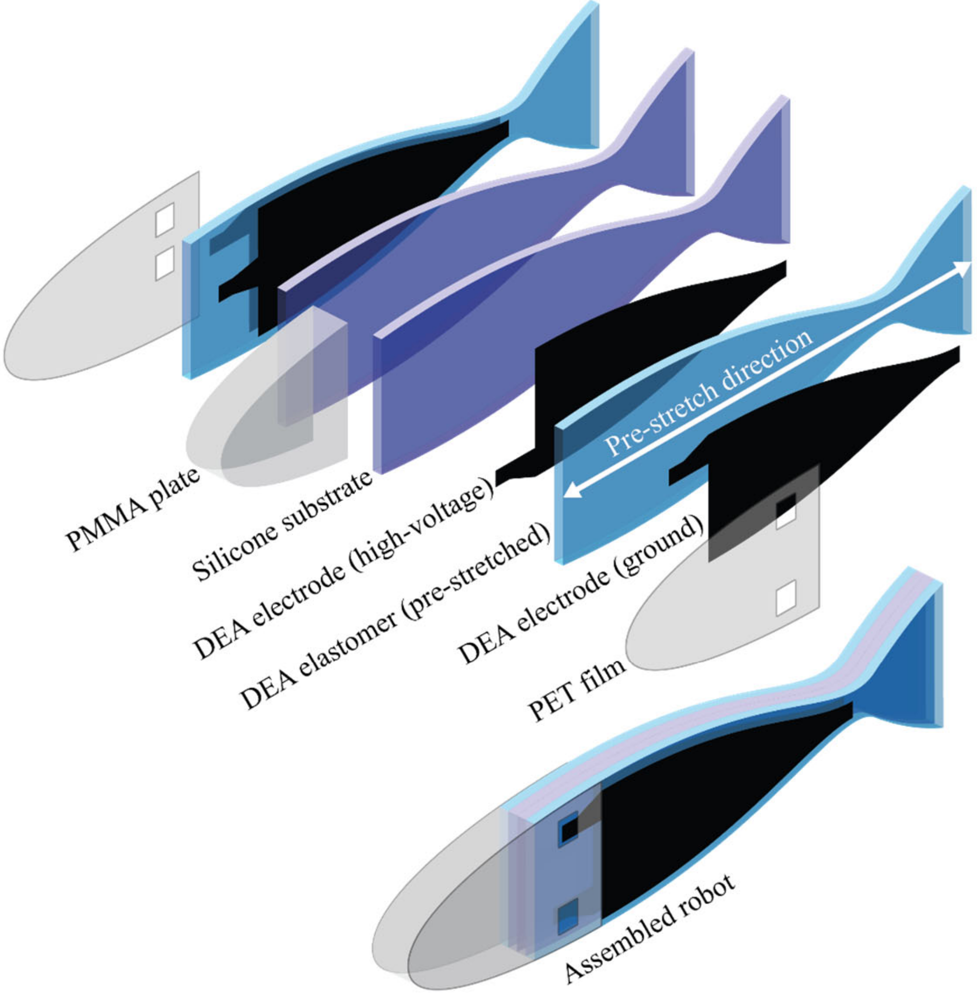


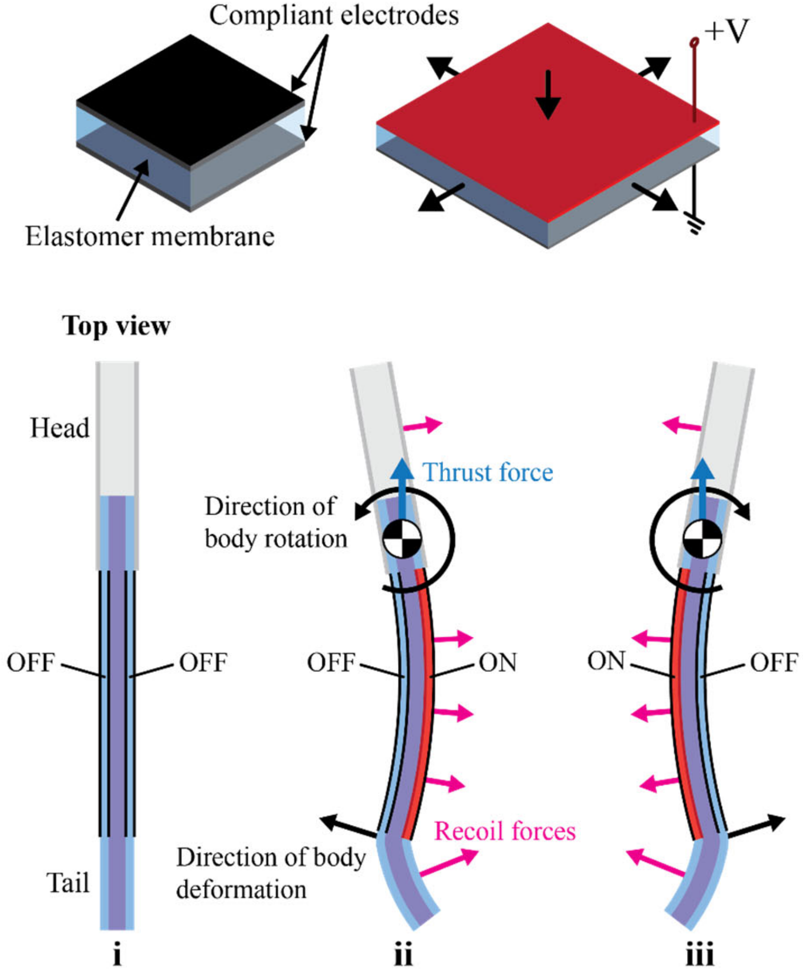
Structural composition of the gripper

J. Shintake et al., *Adv. Mater.* **2016**, *28*, 231.

Biomimetic underwater robot

DEAs can be used underwater when insulation measures are taken.



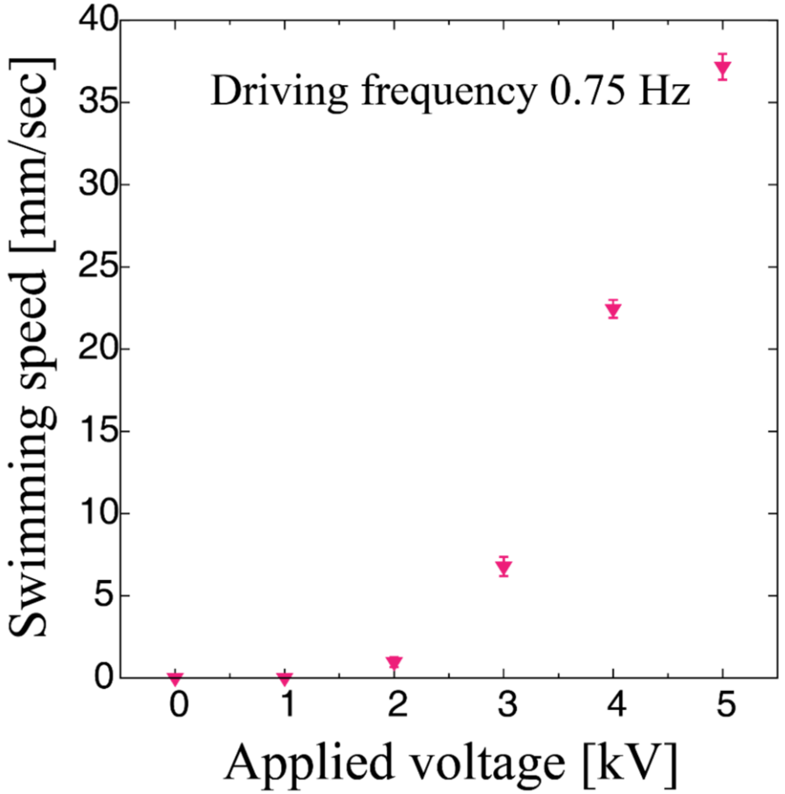


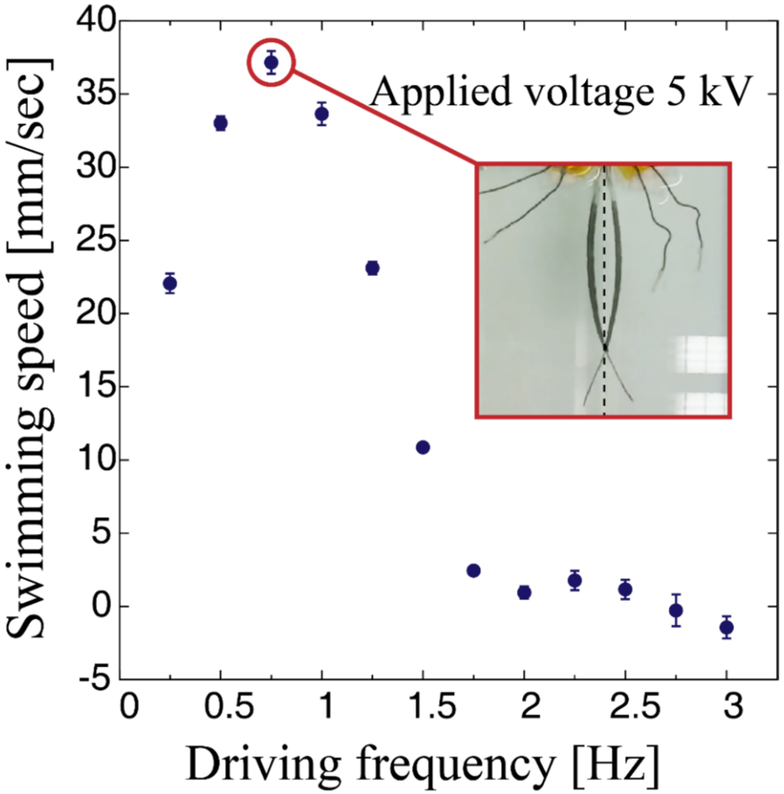
Shintake, Jun, et al. "Soft biomimetic fish robot made of dielectric elastomer actuators." *Soft robotics* 5.4 (2018): 466-474.

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

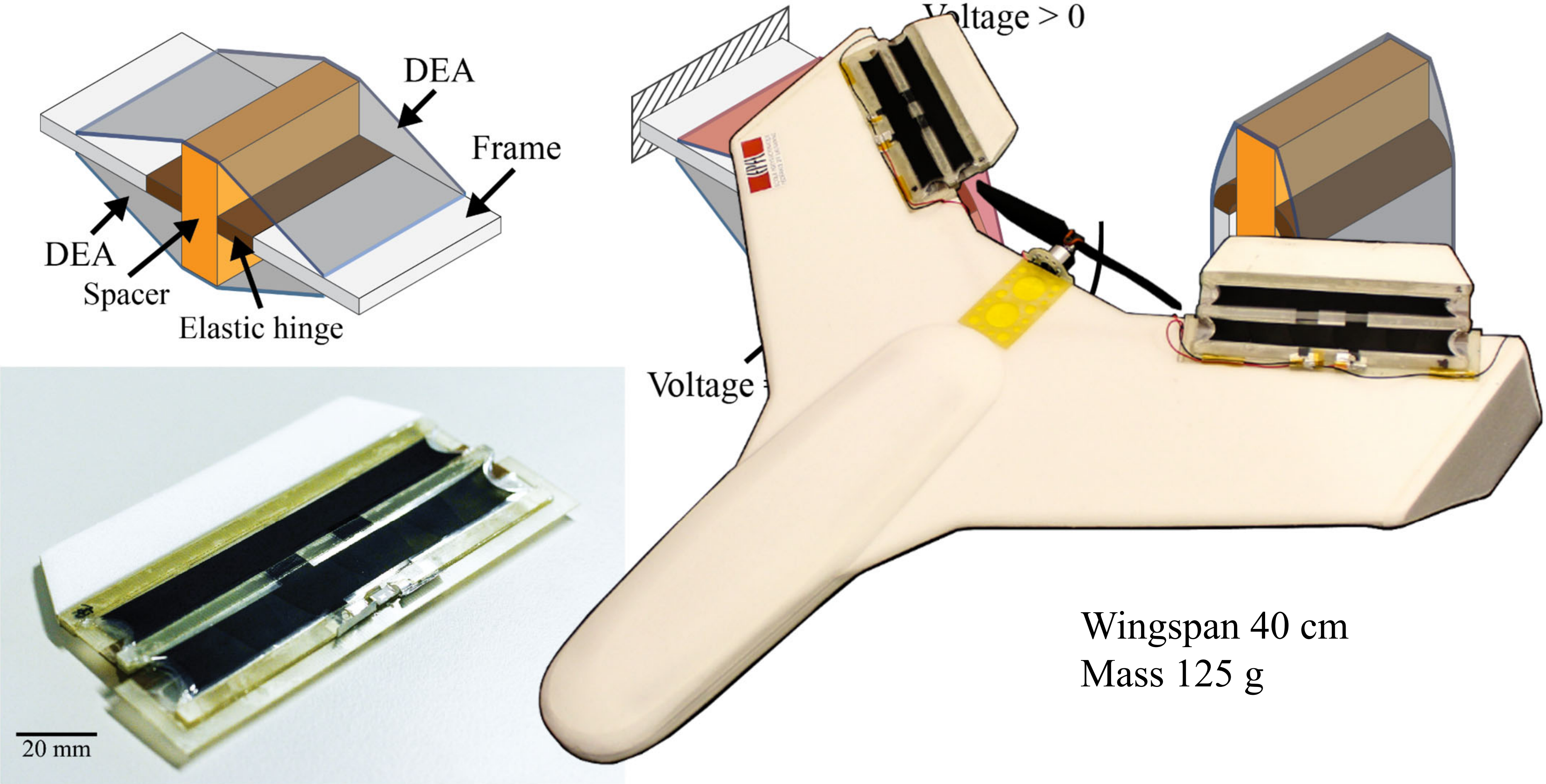




J. Shintake et al., *Soft Robot.* **2018**, *5*, 466.
J. Shintake et al., in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, Daejeon, Korea, **2016**.

Flying robot with foldable actuators

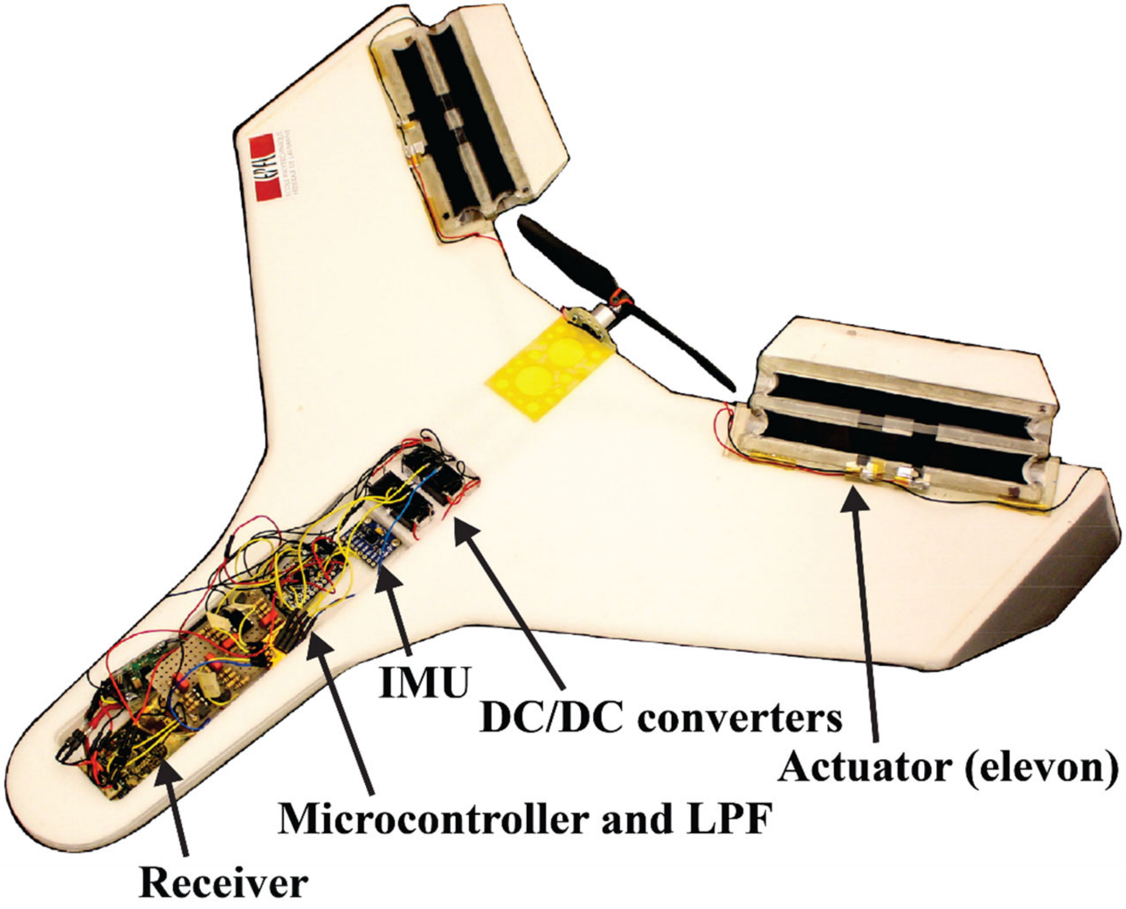
Foldable function enables shape change of robots to improve portability

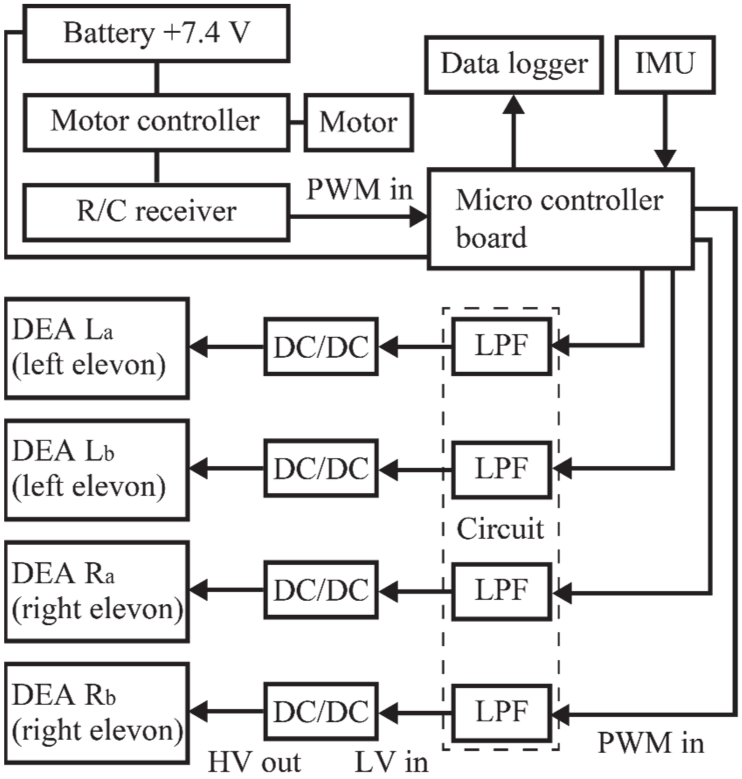


Wingspan 40 cm
Mass 125 g

J. Shintake et al., *IEEE/ASME Trans. Mechatronics* **2015**, *20*, 1997.

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

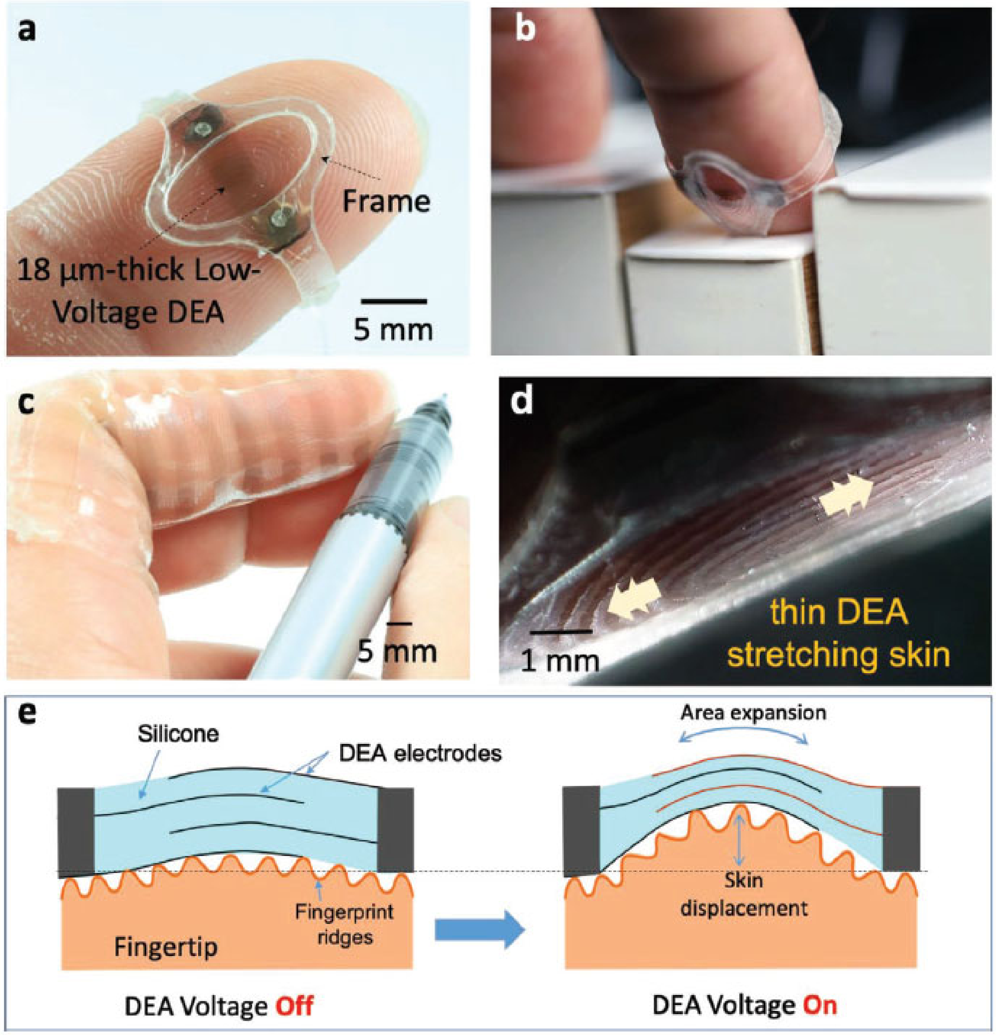


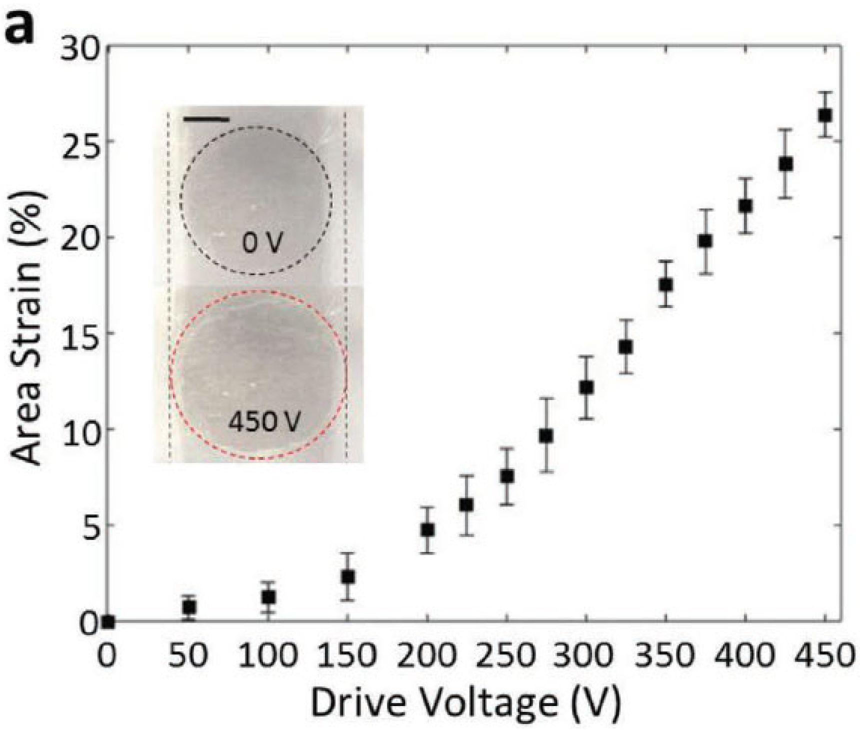


Each DC/DC converter weighs 4.2 g (0-5000V output)

Examples from other studies

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

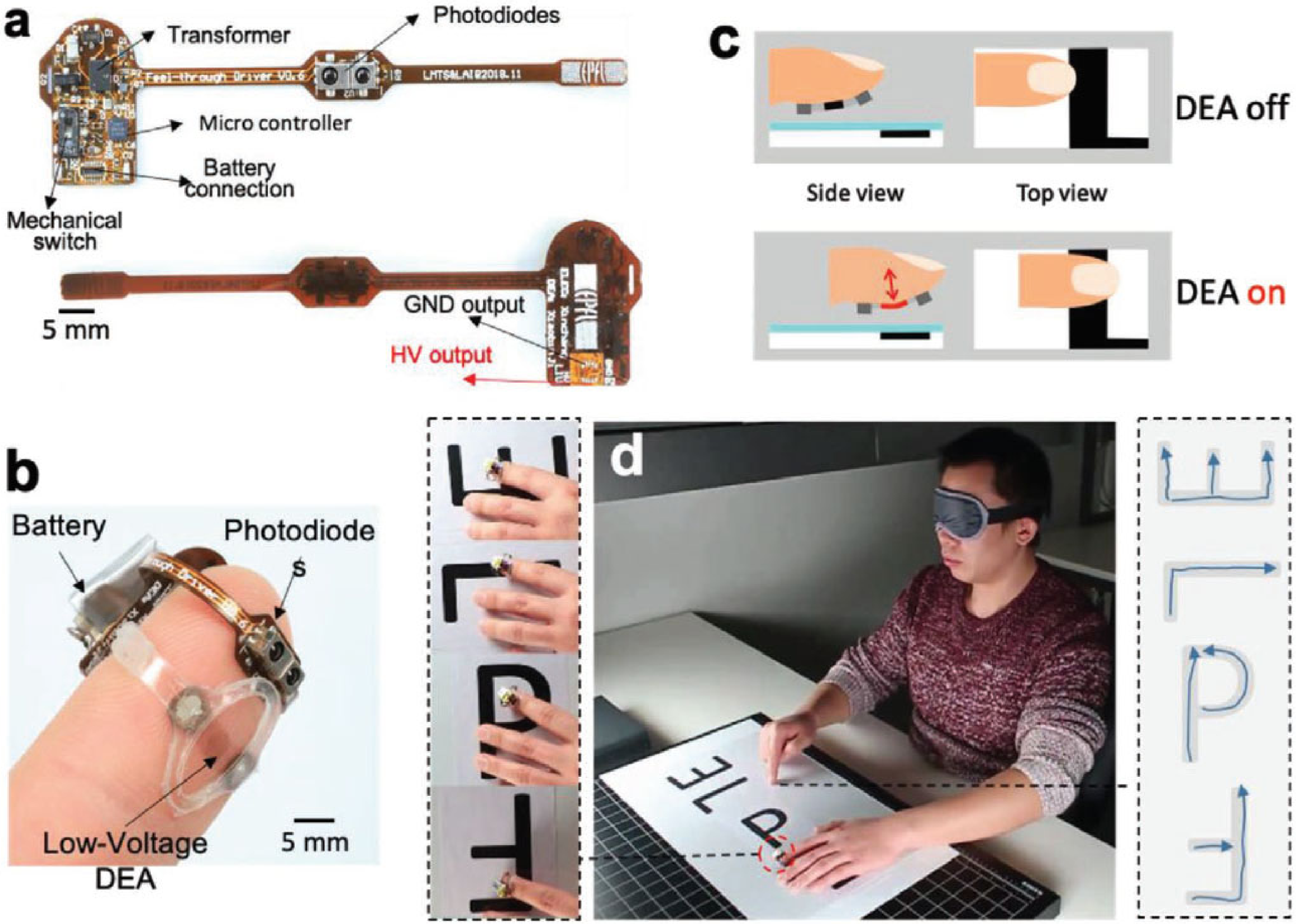




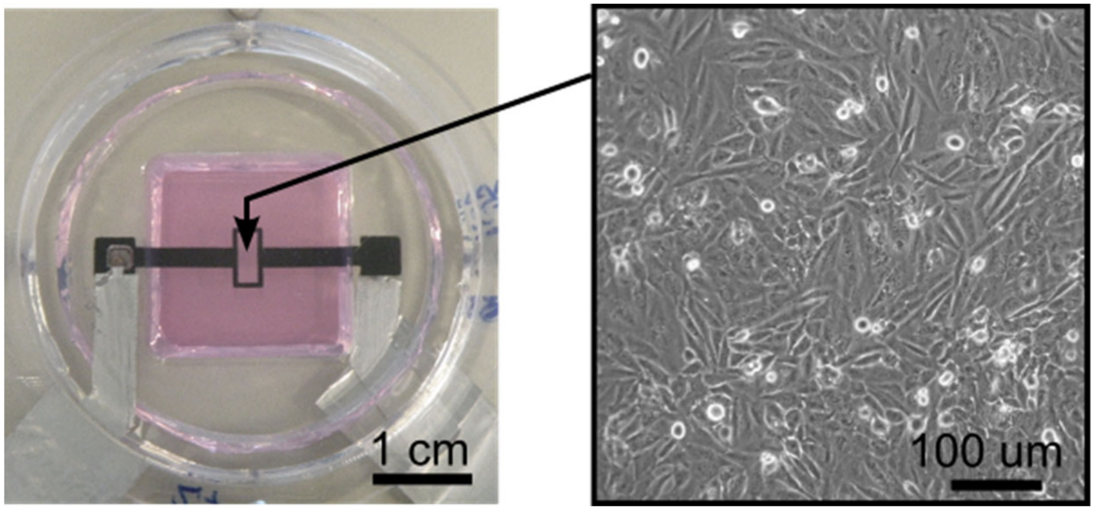
Ji, Xiaobin, et al. "Untethered Feel-Through Haptics Using 18-µm Thick Dielectric Elastomer Actuators." *Advanced Functional Materials*: 2006639.

Examples from other studies

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

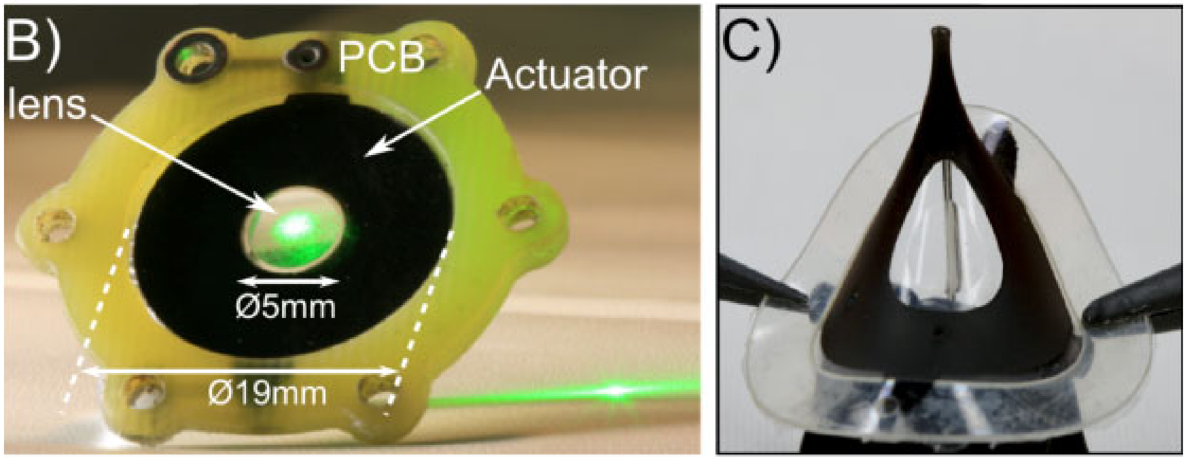


Examples from other studies



Device to measure mechanical properties of living cells

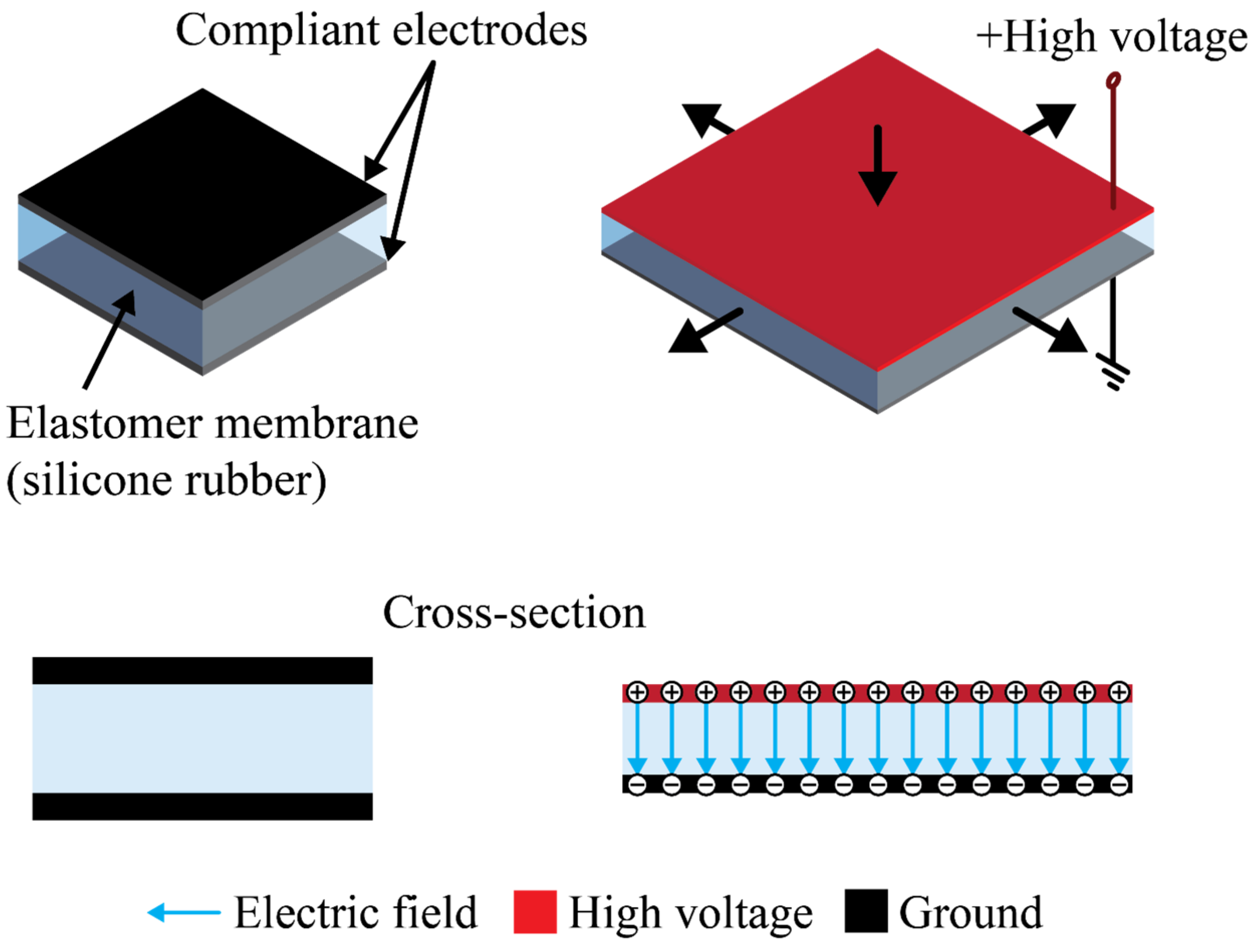
Poulin, Alexandre, et al. "An ultra-fast mechanically active cell culture substrate." *Scientific reports* 8.1 (2018): 1-10.



Soft lens

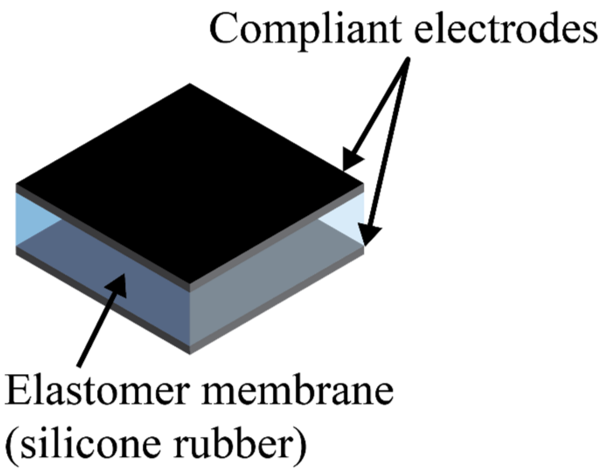
Maffli, Luc, et al. "Ultrafast all-polymer electrically tunable silicone lenses." *Advanced functional materials* 25.11 (2015): 1656-1665.

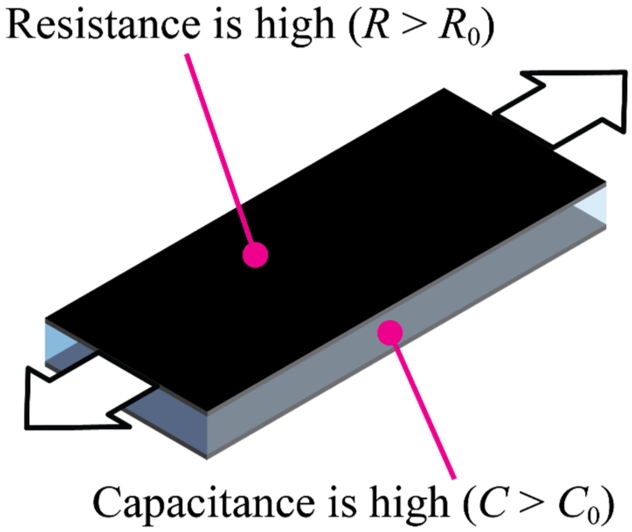
Dielectric elastomer actuators (DEAs)

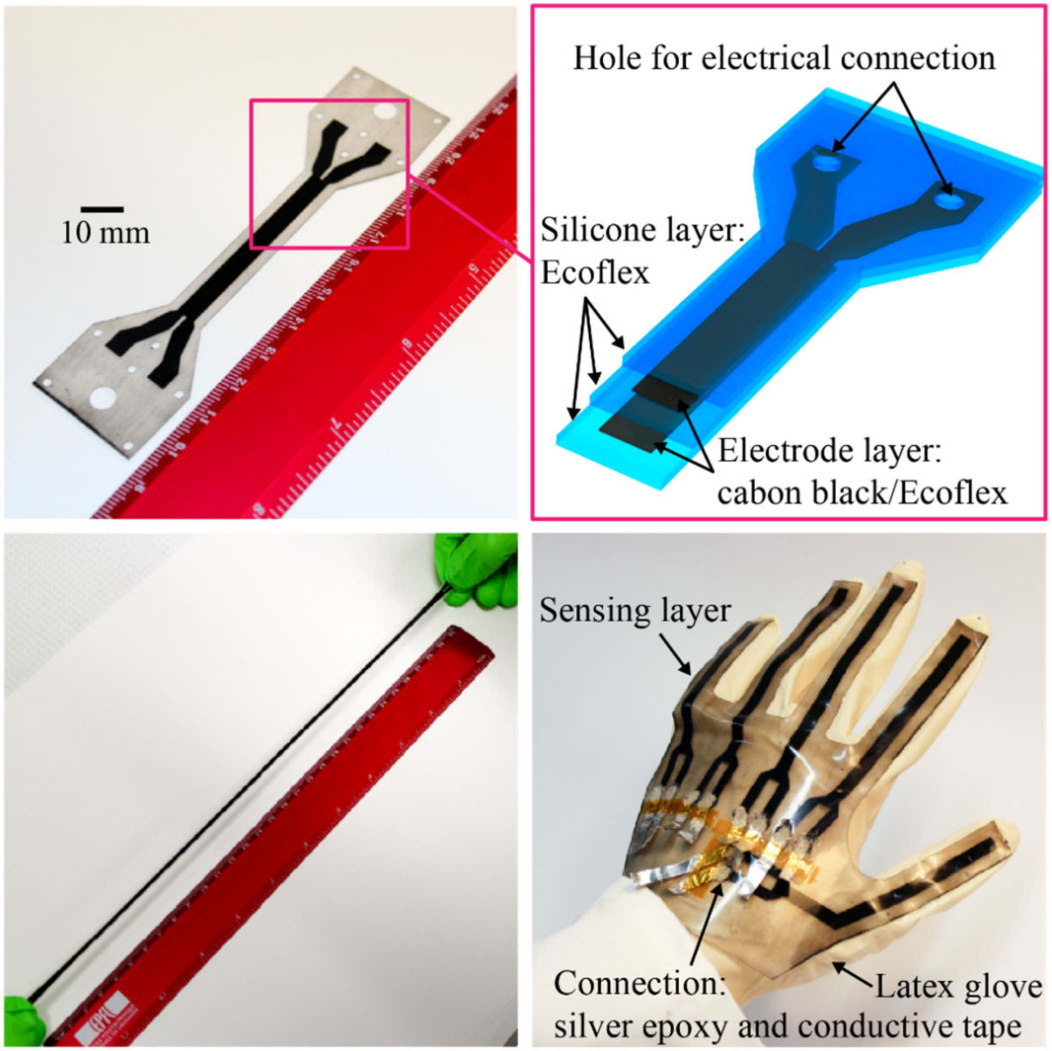


- **Simple**
- **Soft (elastic modulus is ~1 MPa)**
- **Fast (can be actuated at ~1 kHz)**
- **Large actuation strain (~100 % linear stroke)**
- **High voltage (a few kV)**
- **Self-sensing**

Sensing aspect of DEAs:
Wearable sensors capable of detecting strains 500%

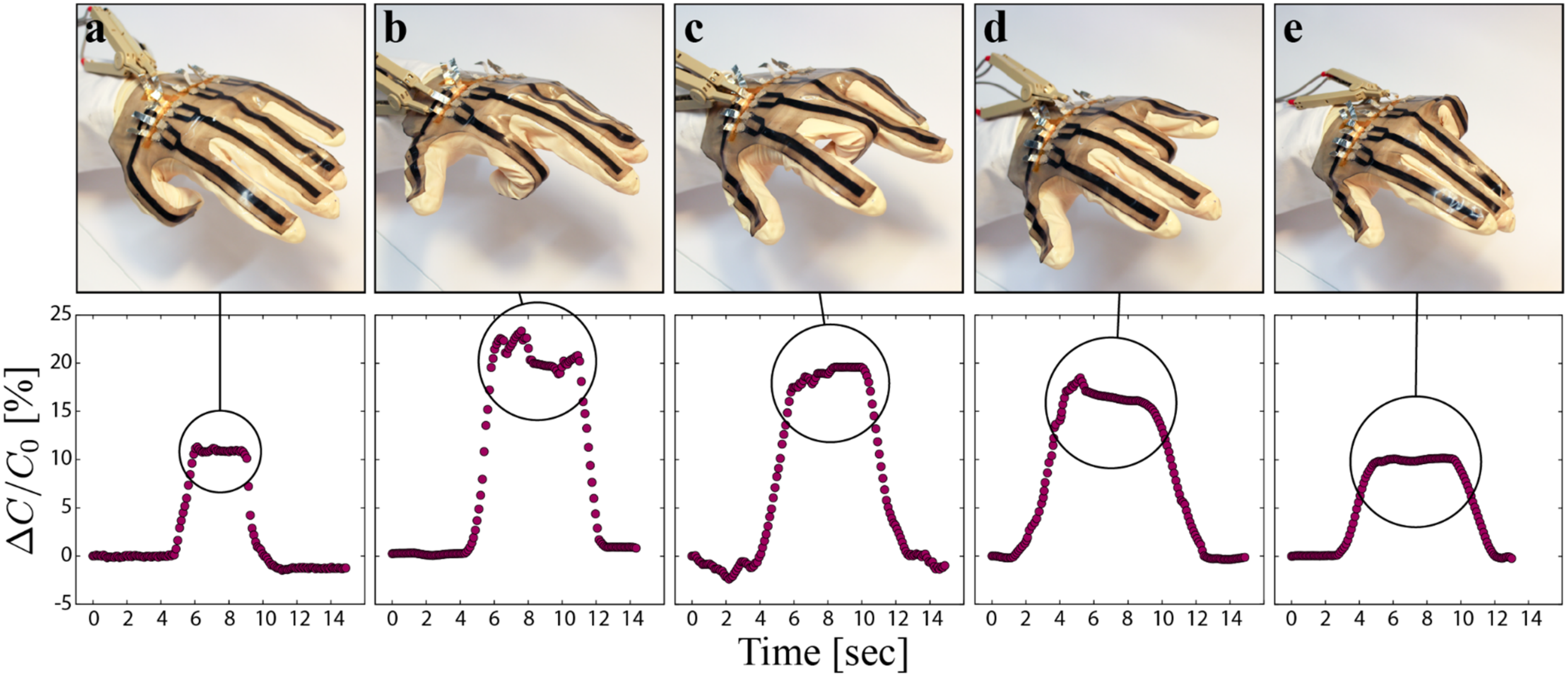






J. Shintake et al., *Adv. Mater. Technol.* **2017**, *3*, 1700284.

Demonstration of intelligent glove with distributed sensors

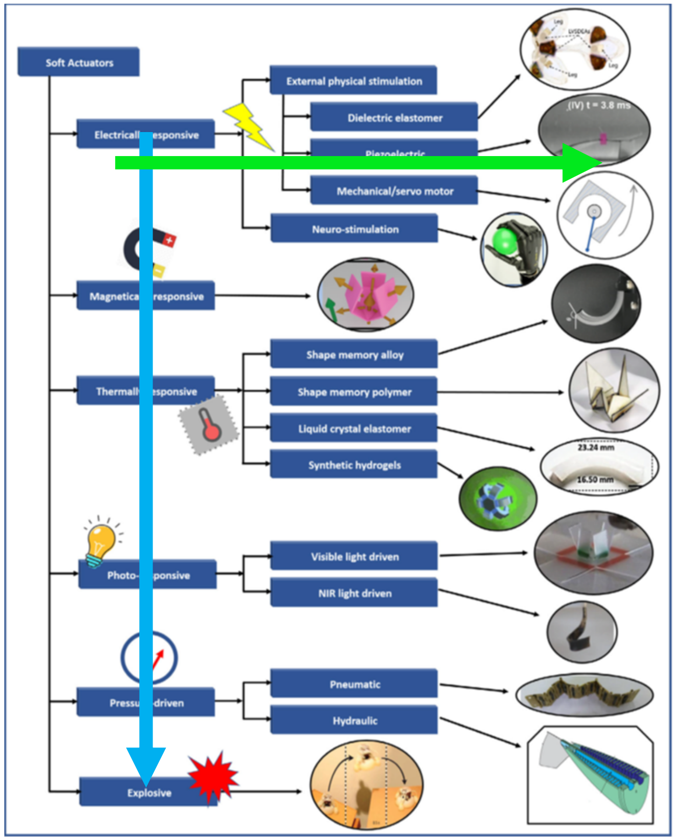


J. Shintake et al., *Adv. Mater. Technol.* **2017**, *3*, 1700284.

Aim of the topic “Soft Actuators”

11/17: Detail a single soft actuator technology and describe how it enables various actuator configurations and robotic systems.

11/24: Overview existing soft actuators and discuss their pros and cons, followed by homework.

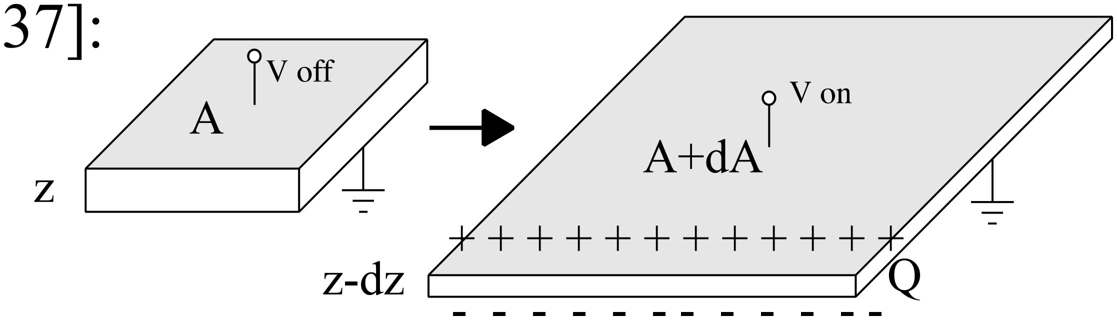


El-Atab, Nazek, et al. "Soft actuators for soft robotic applications: A review." Advanced Intelligent Systems 2.10 (2020): 2000128.

Appendix

DEA Theory

- Electrostatic Pressure [37]:



Capacitance: $$C = \frac{\varepsilon_0 \varepsilon A}{z} \tag{1}$$

$\varepsilon_0 =$ permittivity of free space

$\varepsilon =$ relative permittivity

Energy: $$U_e = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}\frac{zQ^2}{\varepsilon_0 \varepsilon A} \tag{2}$$

change in electrical energy

electrical to mechanical conversion of energy (work)

Change in energy:

$$\mathrm{d}U_e = \frac{Q}{C}\mathrm{d}Q + U_e\left\{\left(\frac{1}{z}\right)\mathrm{d}z - \left(\frac{1}{A}\right)\mathrm{d}A\right\} = \boxed{V\,\mathrm{d}Q} + \boxed{U_e\left\{\left(\frac{1}{z}\right)\mathrm{d}z - \left(\frac{1}{A}\right)\mathrm{d}A\right\}} \tag{3}$$

DEA Theory

- Electrostatic Pressure [37 ch. 1]:

Constant volume assumption: $Az = Vol \quad \Rightarrow \quad \mathrm{d}Vol = A\,\mathrm{d}z + z\,\mathrm{d}A = 0$ (4)

Simplifying (3): $\mathrm{d}U_e = V\,\mathrm{d}Q - 2U_e\left(\frac{1}{A}\right)\mathrm{d}A = V\,\mathrm{d}Q + 2U_e\left(\frac{1}{z}\right)\mathrm{d}z$ (5)

Compressive stress p is defined as:

$$-Ap\,\mathrm{d}z = \mathrm{d}W \quad \Rightarrow \quad p = \left(\frac{1}{A}\right)\frac{\mathrm{d}U_e}{\mathrm{d}z} \quad (\text{constant charge}) \tag{6}$$

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

$$\boxed{p = \varepsilon_0\varepsilon\left(\frac{V}{z}\right)^2 = \varepsilon_0\varepsilon E^2}$$

Electrostatic pressure (7)
(Maxwell stress)

DEA Theory

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

Strain in z: $$S_z = -\frac{p}{Y} = -\frac{\varepsilon_0 \varepsilon}{Y} E^2 = -\frac{\varepsilon_0 \varepsilon}{Y} \left(\frac{V}{z} \right)^2 \qquad (8)$$

$Y = \text{Young's modulus}$

Where z: $$z = z_0 \left(1 + S_z \right) \qquad (9)$$

$z_0 = \text{initial thickness}$

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

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

The real solution to (10):

$$\boxed{\begin{aligned} S_z &= -\frac{2}{3} + \frac{1}{3} \left(H + \frac{1}{H} \right) && (11) \\ H &= \left[\frac{1}{2} \left\{ 2 + 27m + \left(-4 + \left(2 + 27m \right)^2 \right)^{1/2} \right\} \right]^{1/3} && (12) \end{aligned}}$$

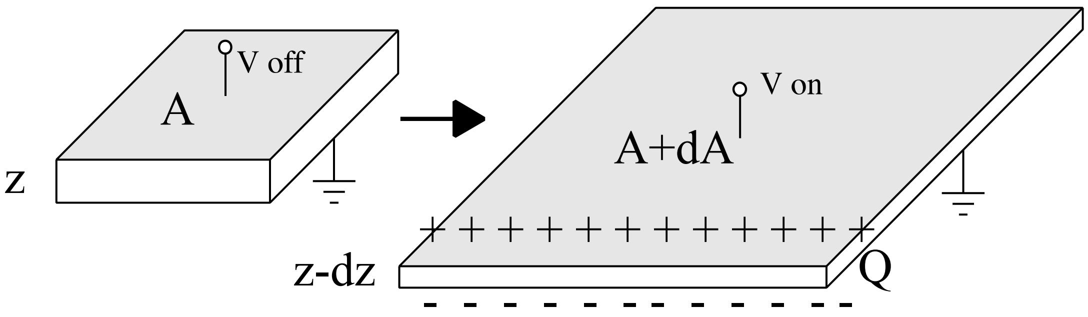
DEA Theory

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

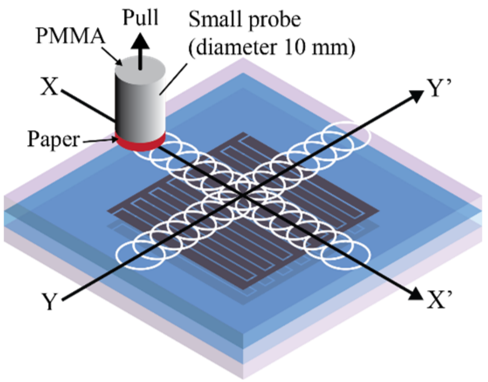
Strain in all directions (constant volume): $$(1+S_x)(1+S_y)(1+S_z)=1 \qquad (13)$$

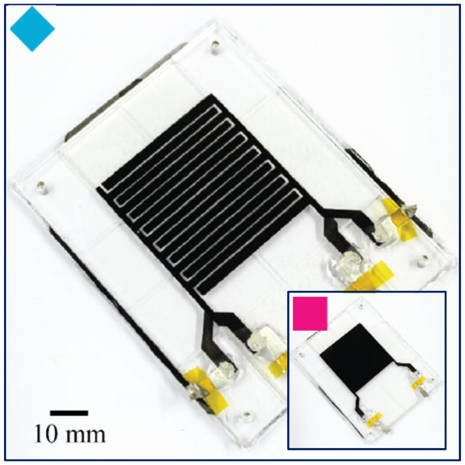
If, $S_x = S_y = S_a$ then, and

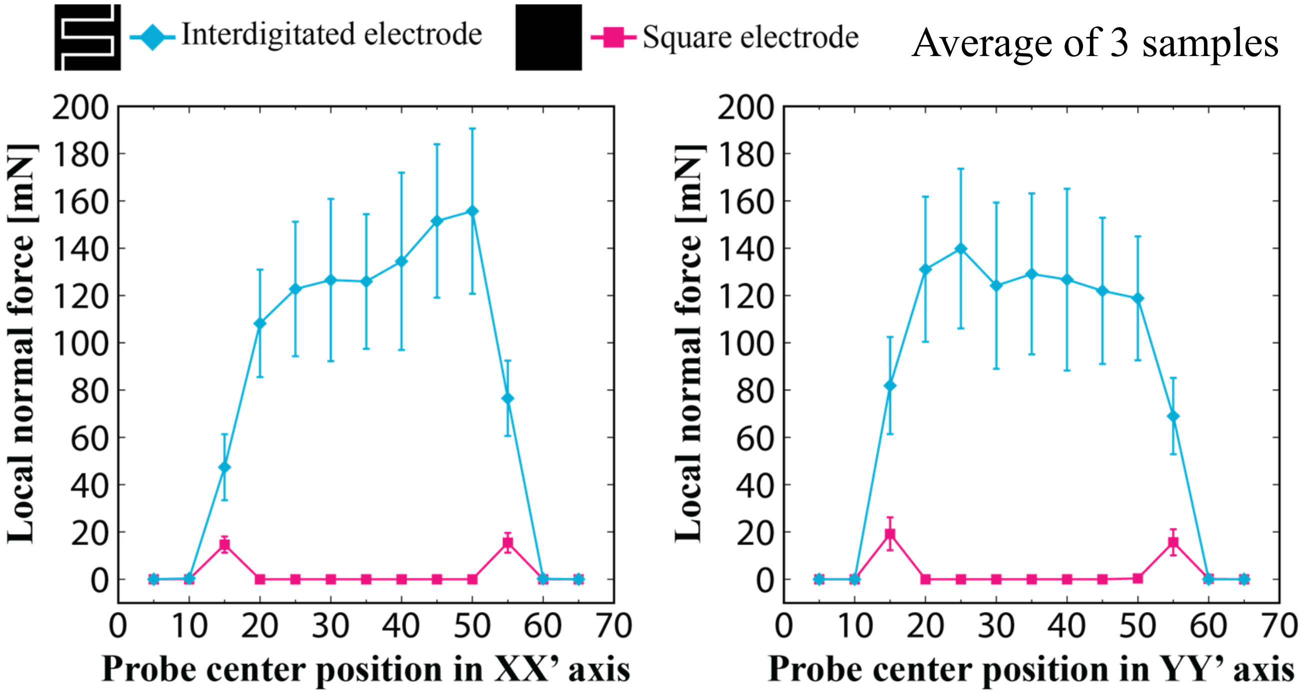
$$\boxed{\begin{aligned} S_a &= (1+S_z)^{-1/2} - 1 && (14) \\ S_z &= -\frac{S_a^2 + 2S_a}{S_a^2 + 2S_a + 1} && (15) \end{aligned}}$$



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







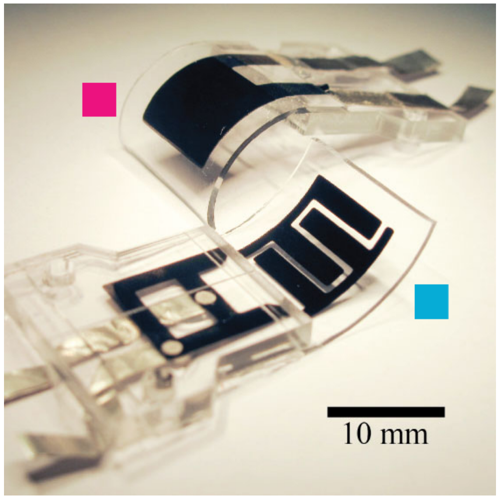
Average of 3 samples

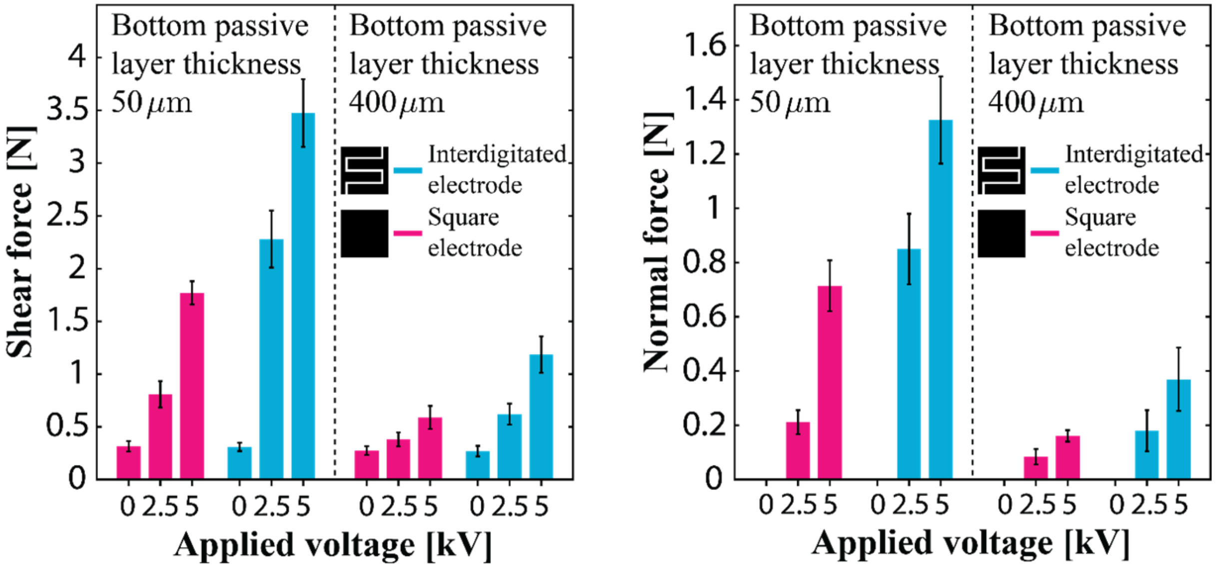
Interdigitated electrode: adhesion force ∝ area, ~2400 mN total
Square electrode: adhesion force ∝ periphery, ~240 mN total

J. Shintake, S. Rosset, B. Schubert, D. Floreano, H. Shea, *Adv. Mater.* 2015, DOI: 10.1002/adma.201504264.

Newton order electroadhesion force represents high holding force of the gripper

Average of 4 samples



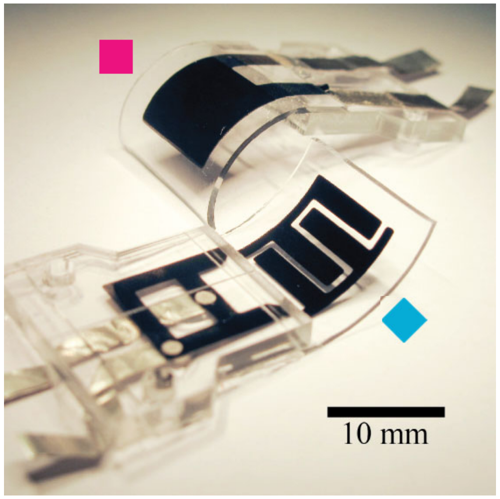


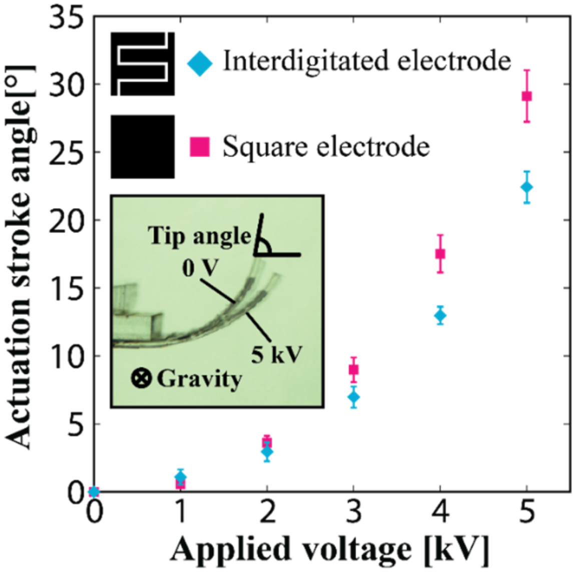
Shear force at 5 kV: 3.5 N for the interdigitated, 1.8 N for the square

- 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.

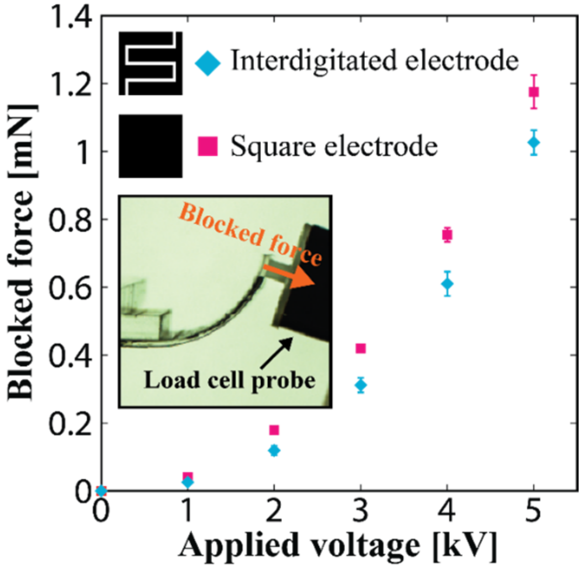
J. Shintake, S. Rosset, B. Schubert, D. Floreano, H. Shea, *Adv. Mater.* 2015, DOI: 10.1002/adma.201504264.

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





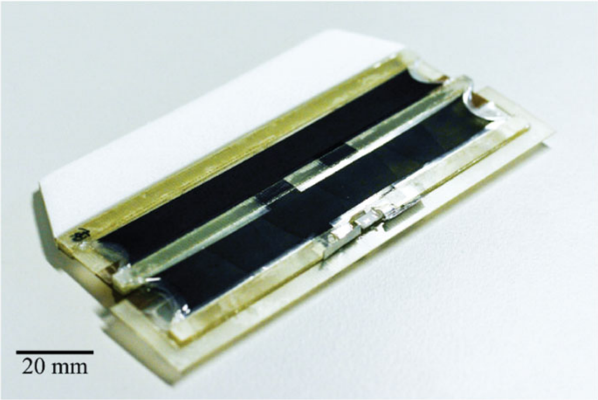
Average of 4 samples

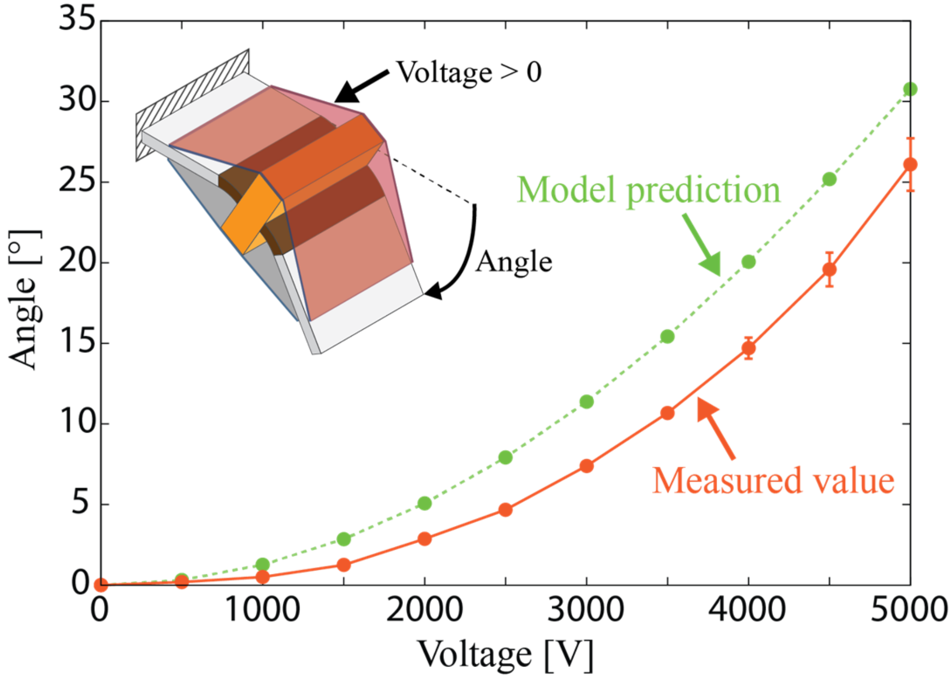


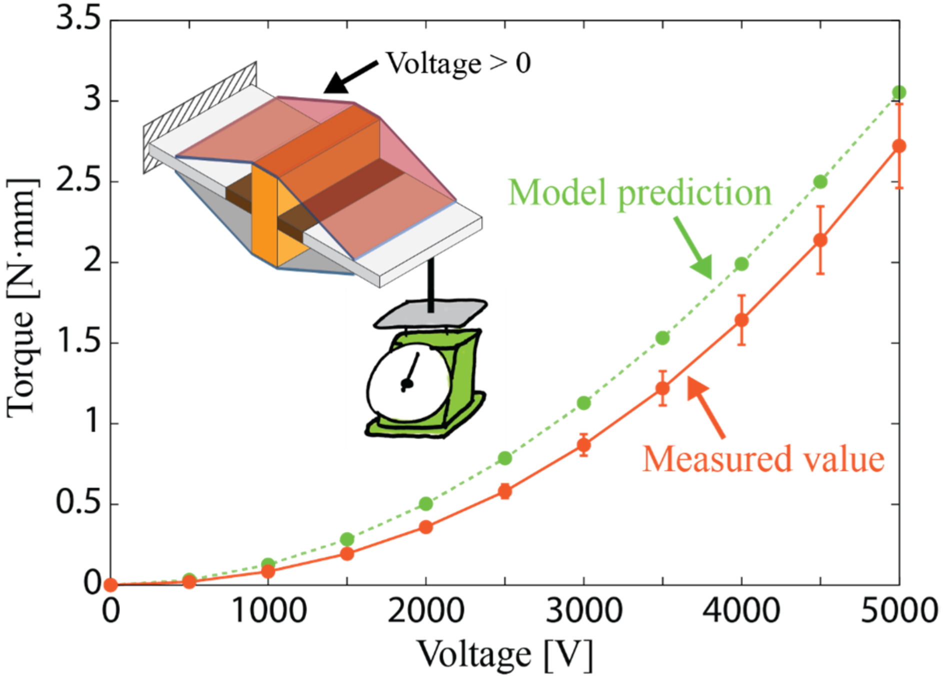
- Actuation stroke at 5 kV: 22 ° for the interdigitated, 29 ° for the square
- Blocked force at 5 kV: 1 mN for the interdigitated, 1.2 mN for the square
- mN order force enables handling of fragile and sensitive objects in the gripper.

J. Shintake, S. Rosset, B. Schubert, D. Floreano, H. Shea, *Adv. Mater.* 2015, DOI: 10.1002/adma.201504264.

Actuator angle and torque can be controlled and predicted



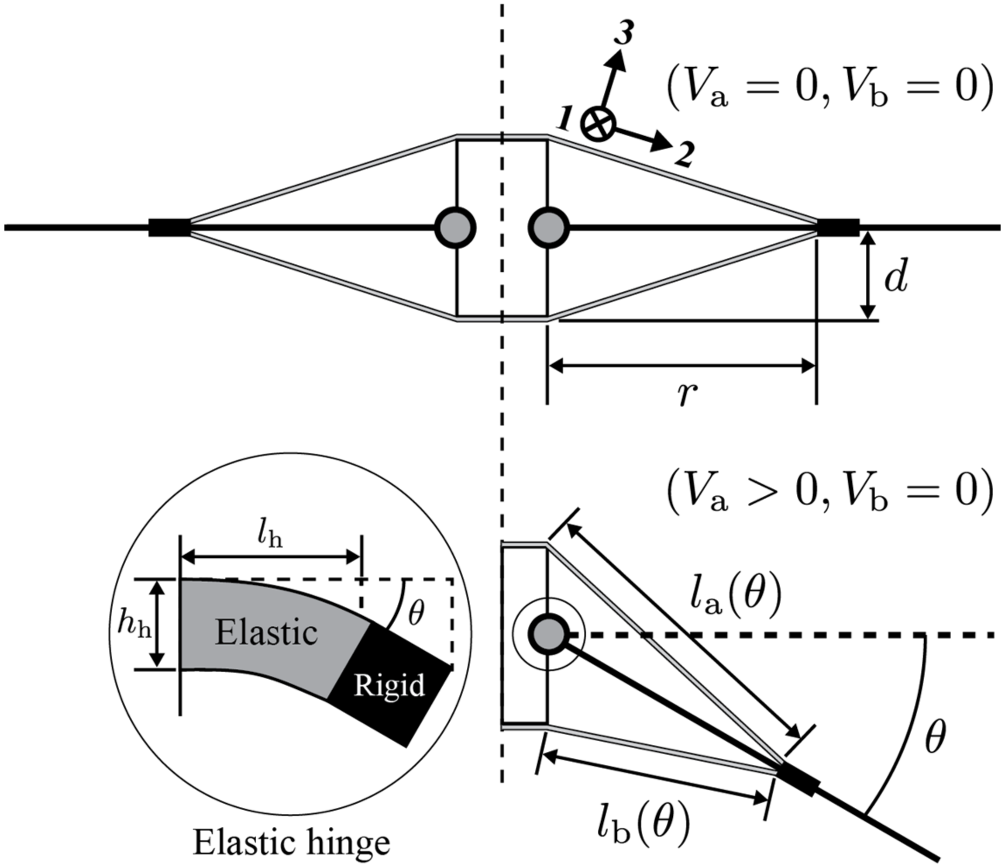




J. Shintake et al., *IEEE/ASME Trans. Mechatronics* **2015**, *20*, 1997.

Analytical model to calculate the bending angle and the torque

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

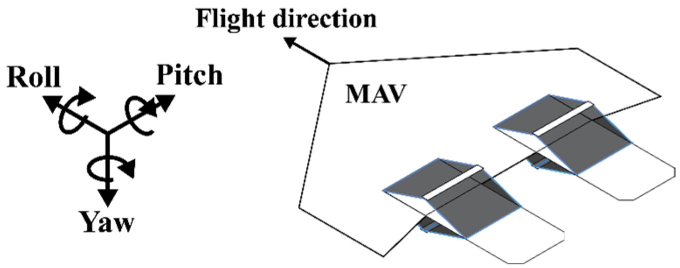


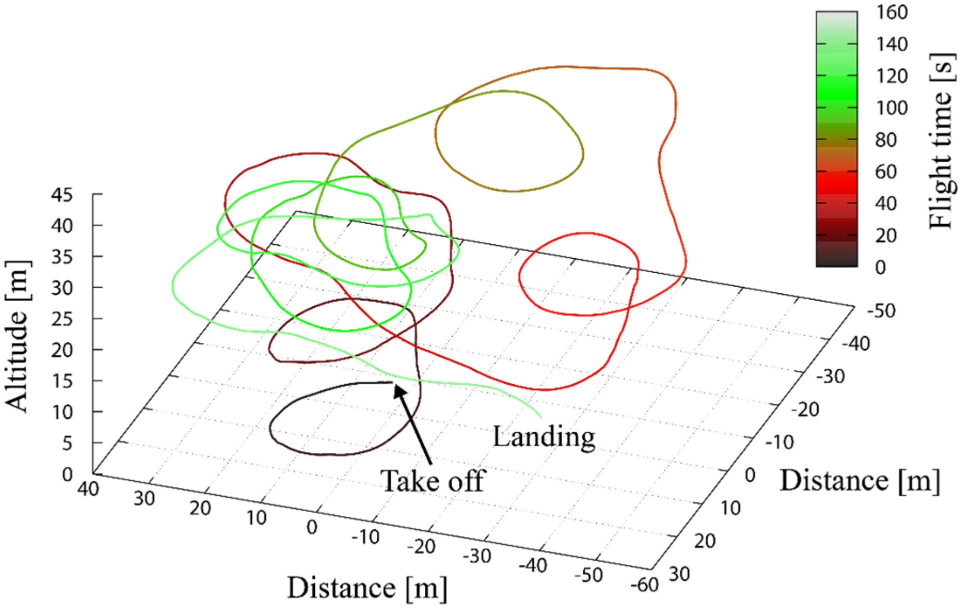
$$W = \sum_{i=1}^{3} C_i (I_1 - 3)^i,$$

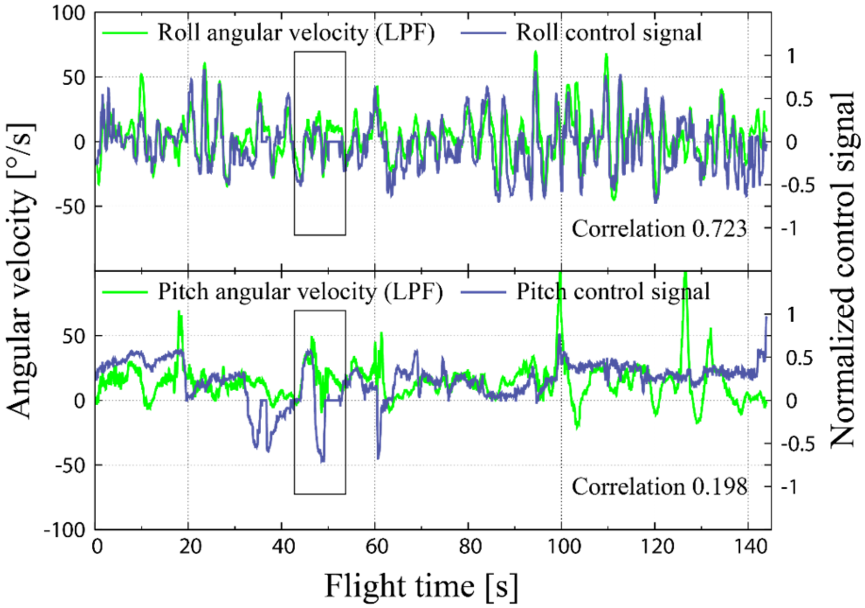
$$p = -\varepsilon_0 \varepsilon_{\mathrm{r}} \frac{V^2}{z^2} = -\varepsilon_0 \varepsilon_{\mathrm{r}} E^2$$

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

The foldable actuators well controlled the drone







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

J. Shintake et al., *IEEE/ASME Trans. Mechatronics* **2015**, *20*, 1997.

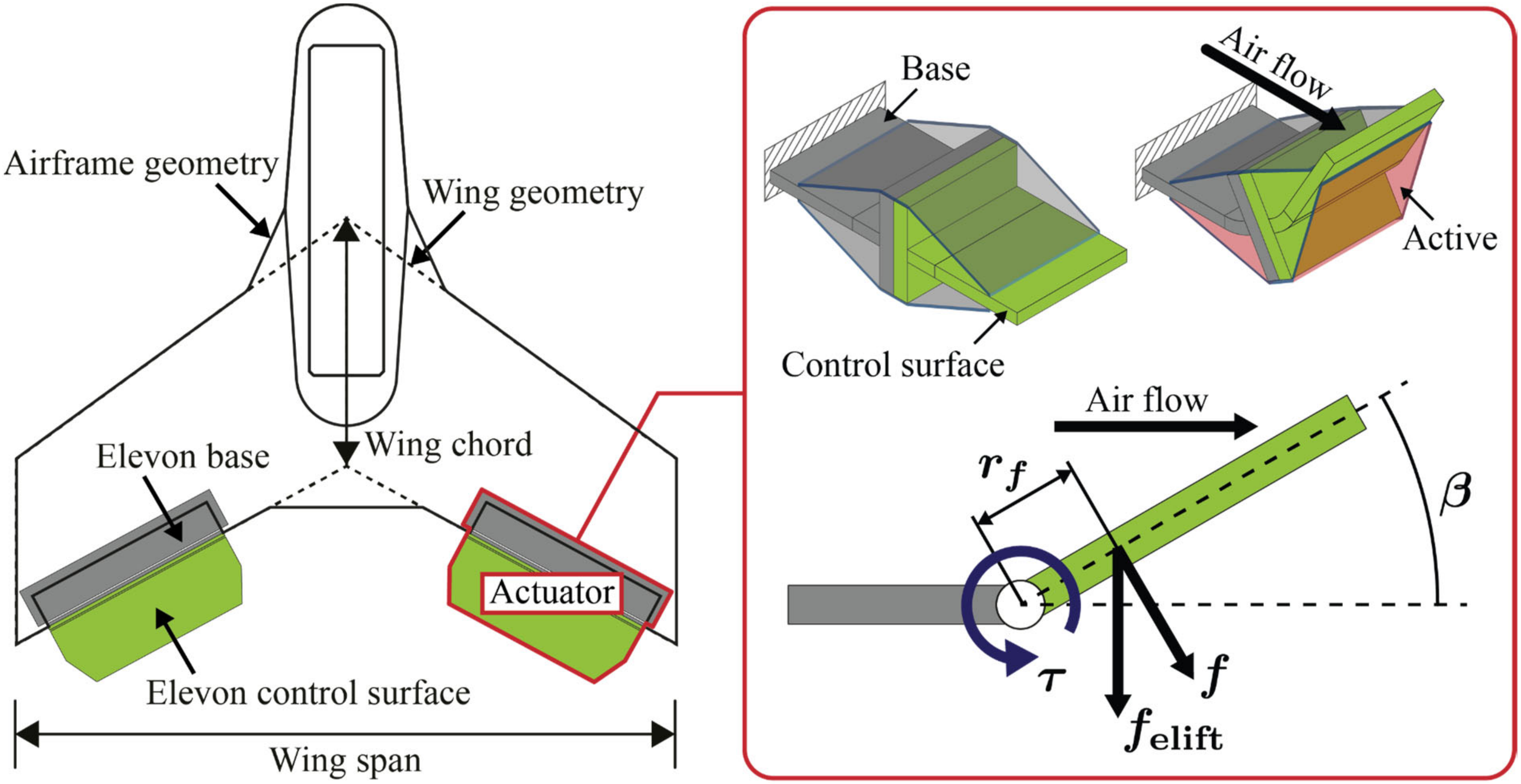

Airframe geometry
Wing geometry
Wing chord
Elevon base
Actuator
Elevon control surface
Wing span
Base
Air flow
Active
Control surface
Air flow
r_f
β
τ
f
f_{elift}

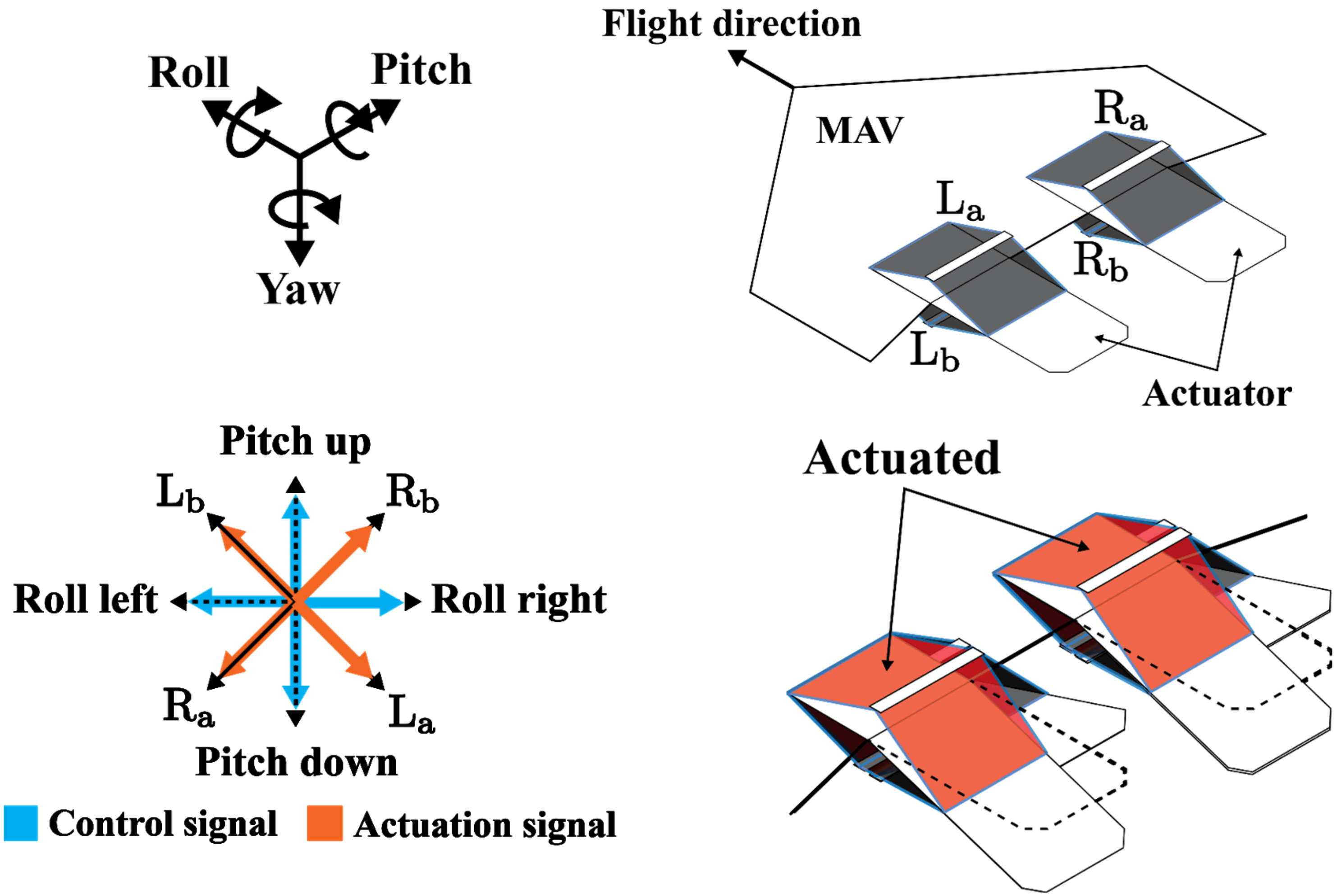
Table 4.1 – Design parameter and specifications of the elevon actuator

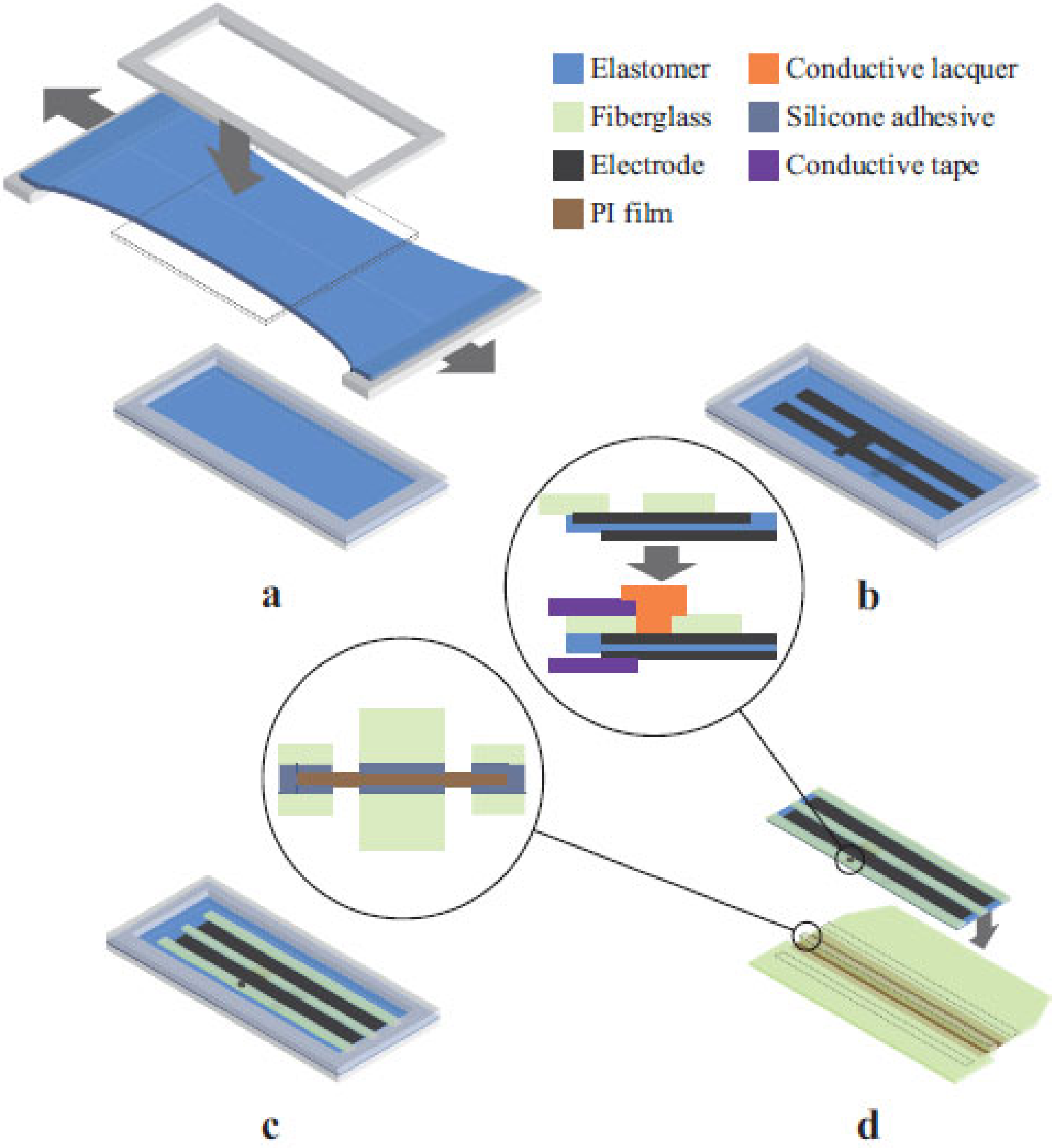
Design parameter	Value
Dimensions	
DEA (half part)	
Initial length l_0	14.1 mm
Initial width w_0	60 mm
Initial thickness h_0	125 µm
DEA electrode (half part)	
Initial length l_{e0}	11.3 mm
Width w_e	112 mm
Frame	
Arm length r	14.5 mm
Spacer height d^{*1}	1.840 mm (1 DEA) 2.025 mm (2 DEAs)
Spacer area (length × width)	4 mm × 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 × width)	24 mm × 130 mm
Control surface area (length × width)	40 mm × 120 mm

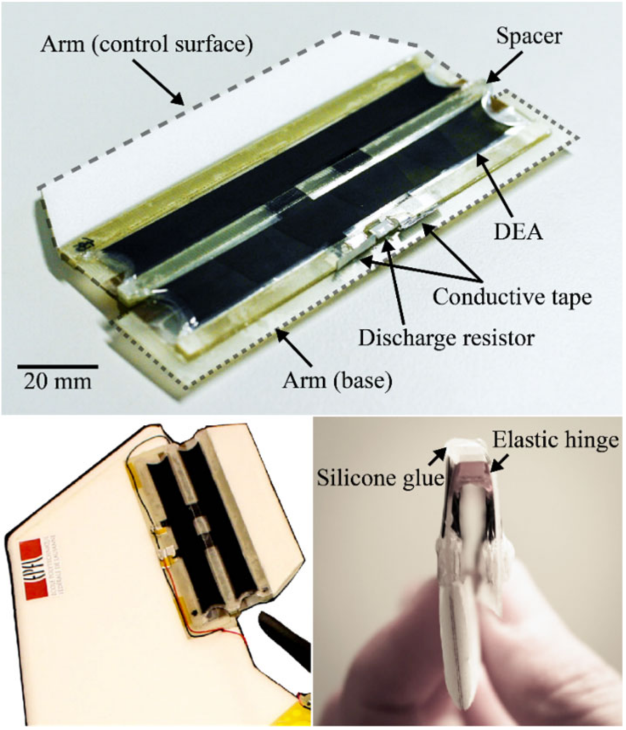
Table 4.2 – Specifications of the MAV

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 · mm

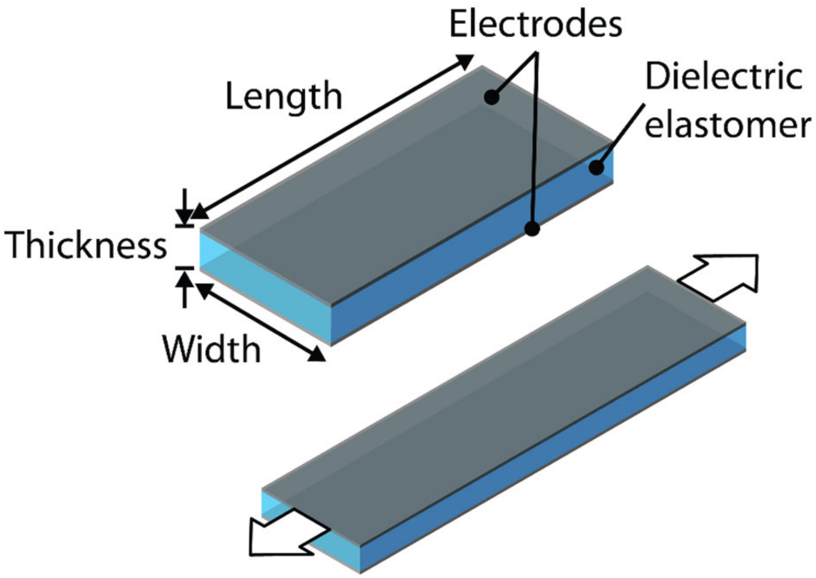
Actuation combination of 4 DEAs provides pitch and roll attitude control

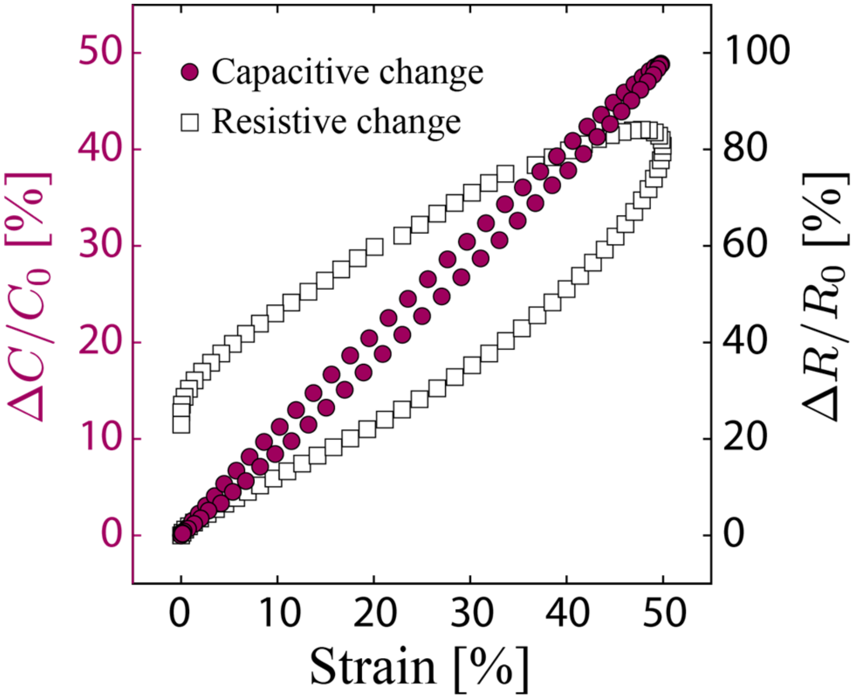



Elastomer
Fiberglass
Electrode
PI film
Conductive lacquer
Silicone adhesive
Conductive tape
a
b
c
d


Arm (control surface)
Spacer
DEA
Conductive tape
Discharge resistor
Arm (base)
20 mm
Elastic hinge
Silicone glue

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



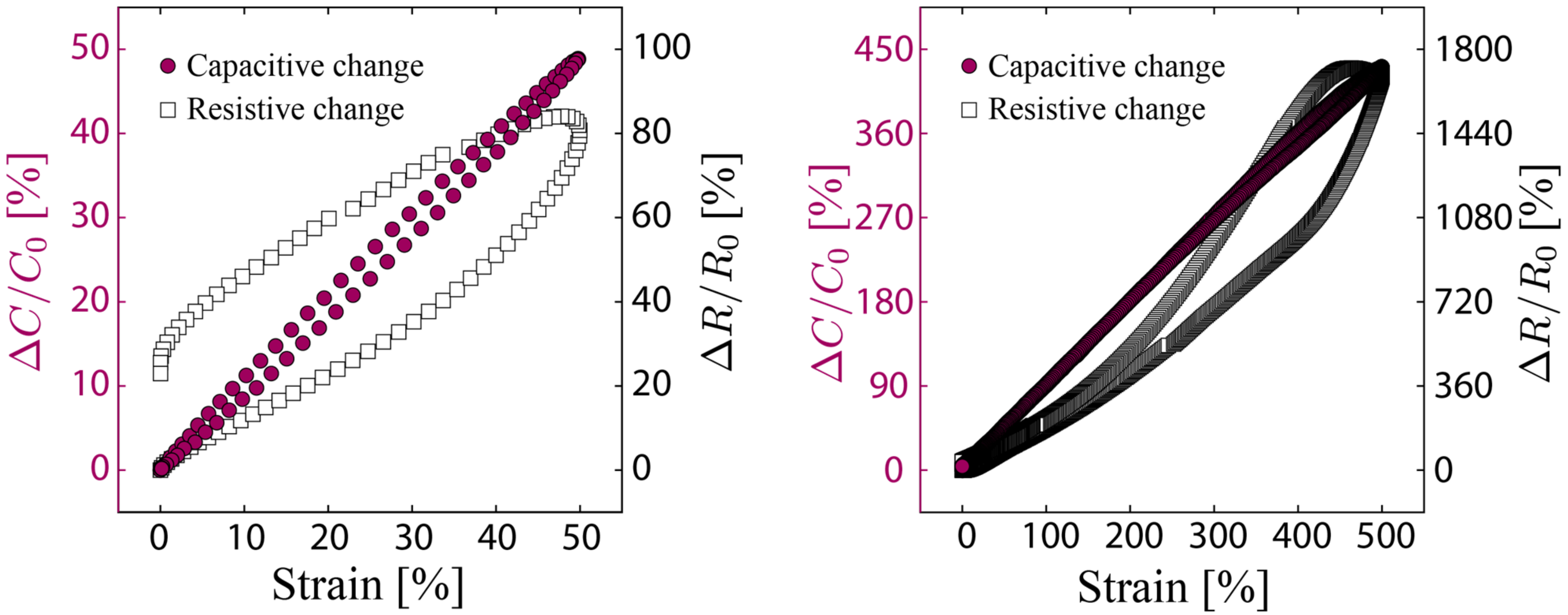


- Capacitive sensing: linear response, low hysteresis, but **low sensitivity**
- Sensitivity, gauge factor (GF):
  - Ratio of relative change in sensor response to the strain
  - In capacitive strain sensors, sensitivity is theoretically **limited to 1**

J. Shintake et al., *Adv. Mater. Technol.* **2017**, *3*, 1700284.

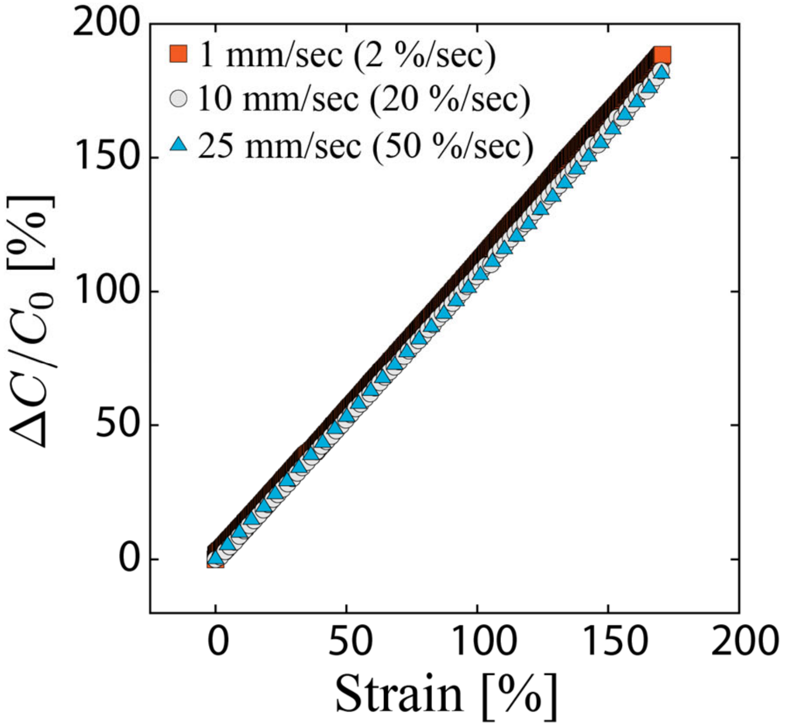
Capacitive sensing showed high linearity and low hysteresis. Resistive sensing had higher sensitivity.

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

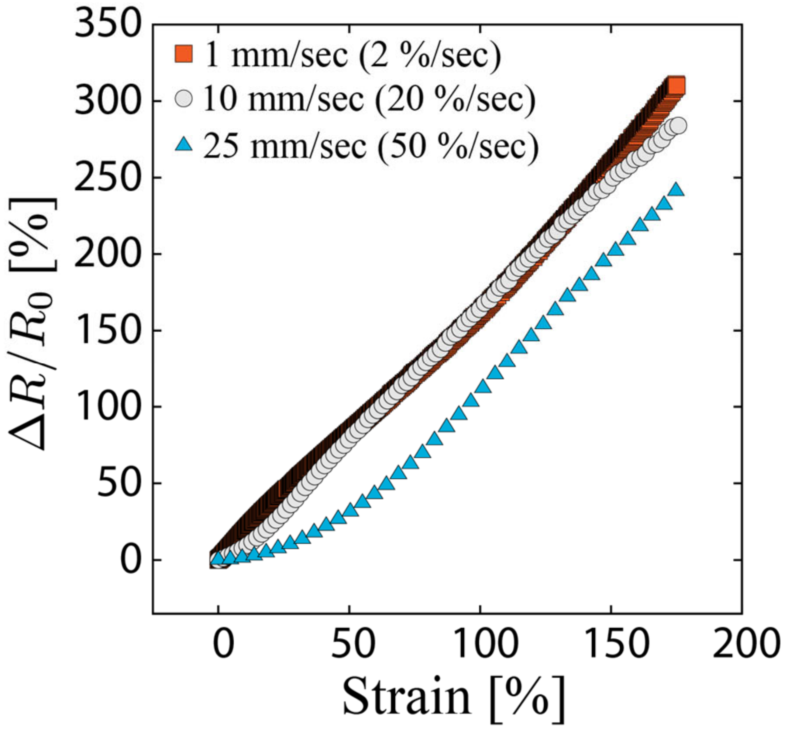


J. Shintake et al., *Adv. Mater. Technol.* **2017**, DOI: 10.1002/admt.201700284.

Capacitive sensing was more stable for different strain speeds



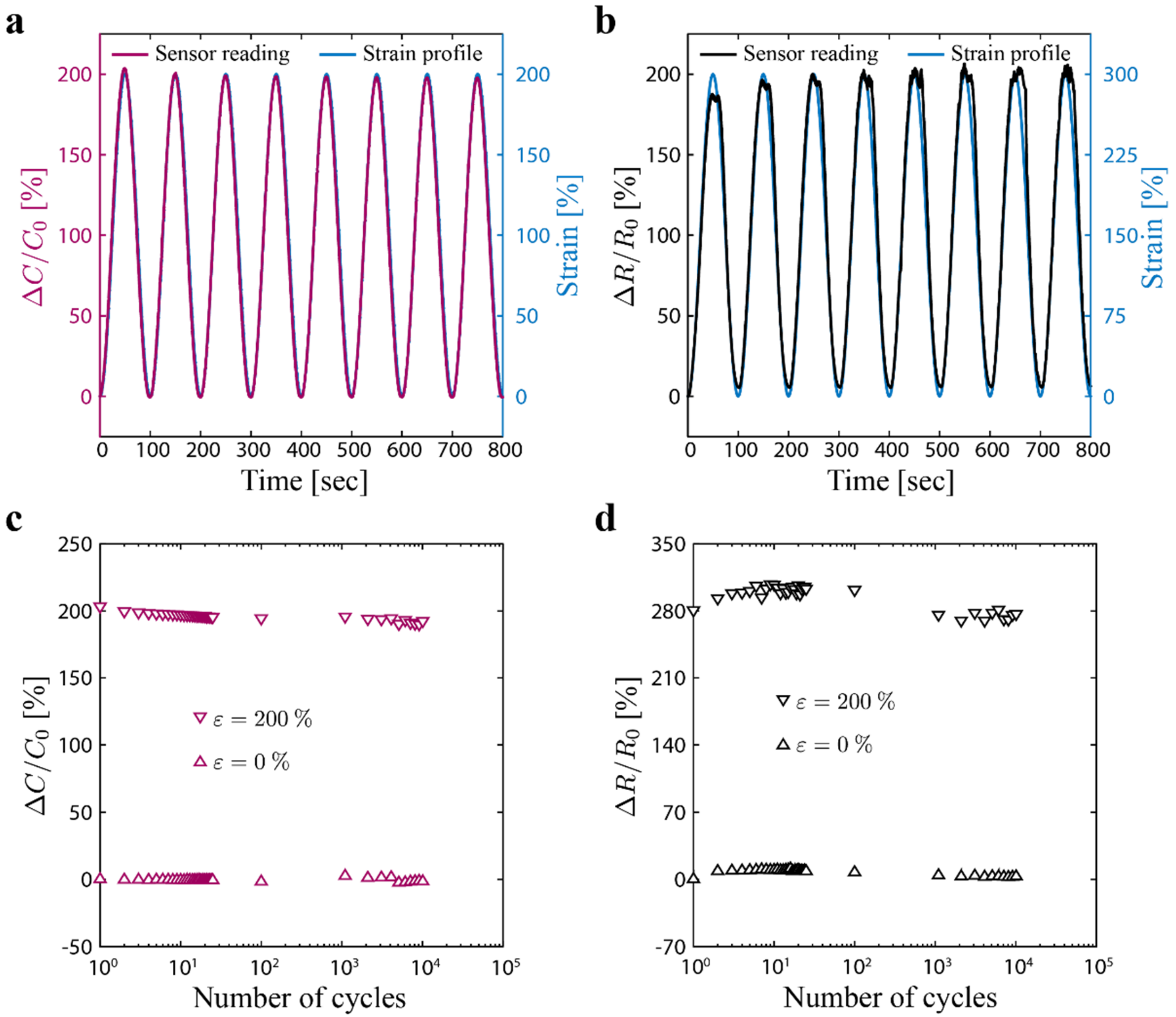
Capacitive sensing

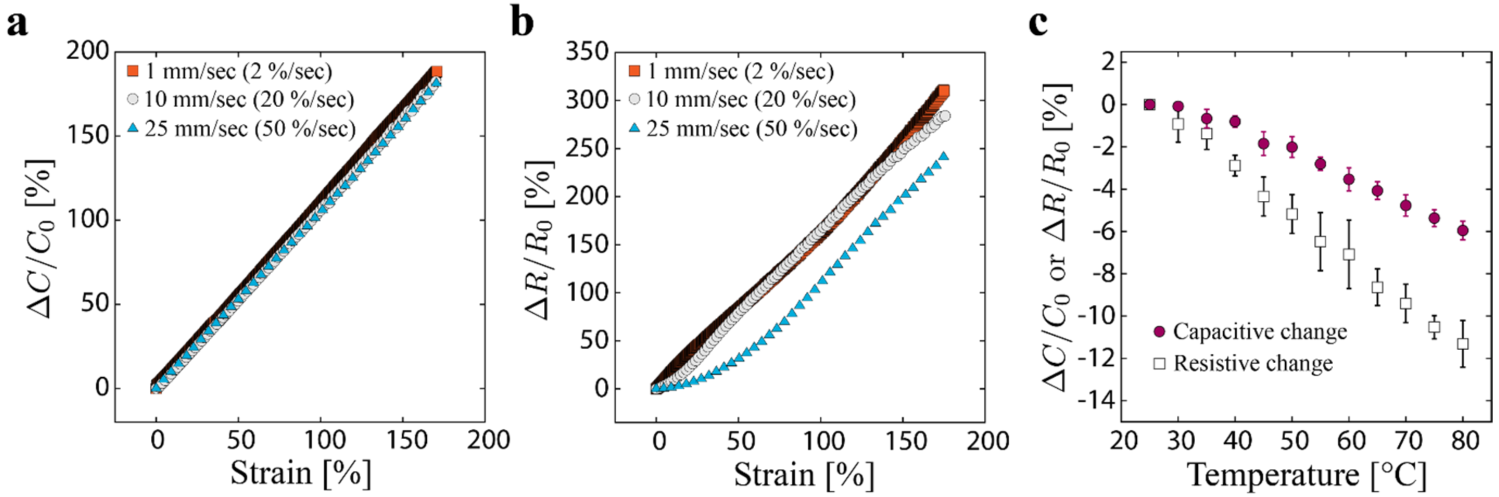


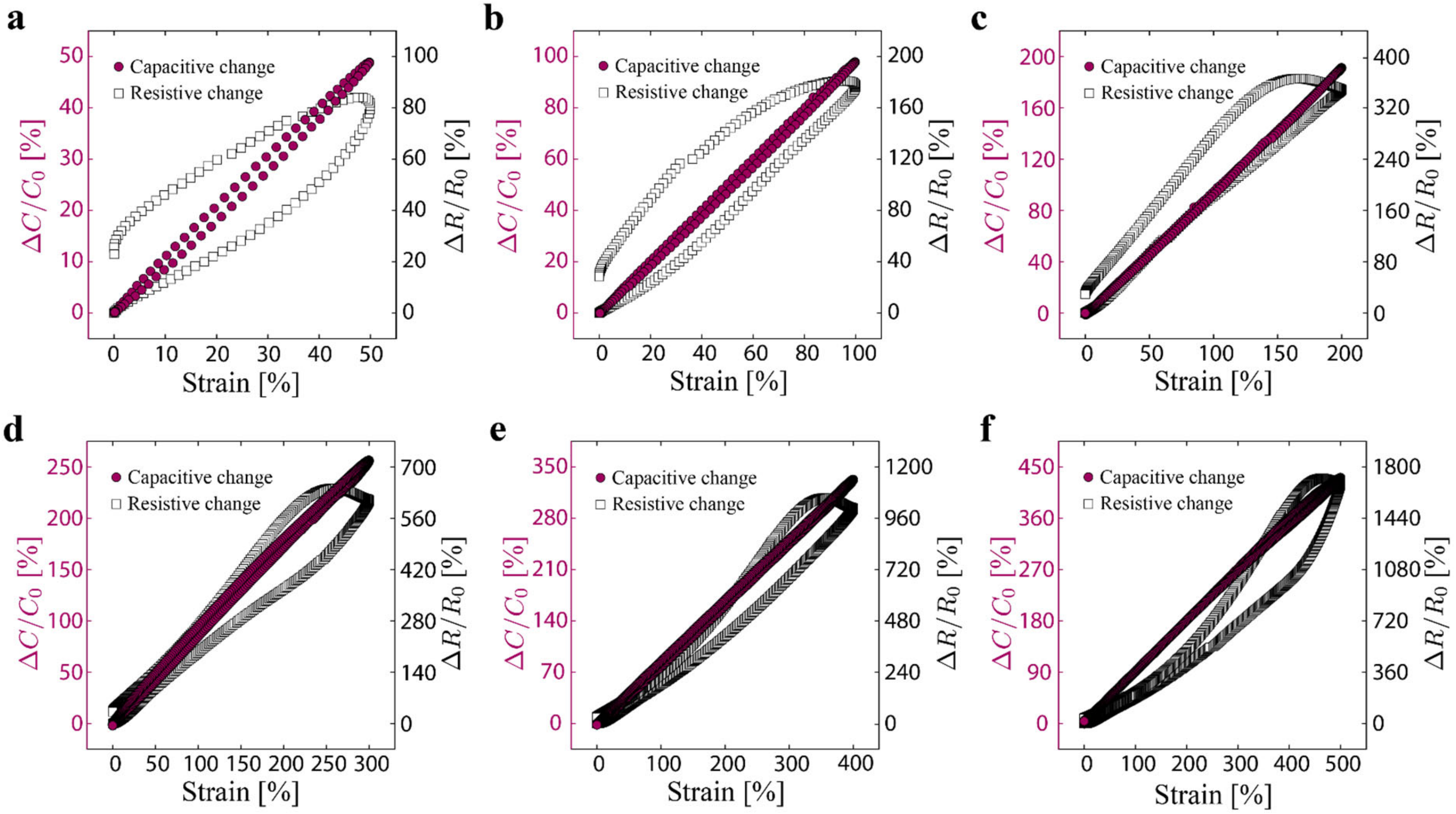
Resistive sensing

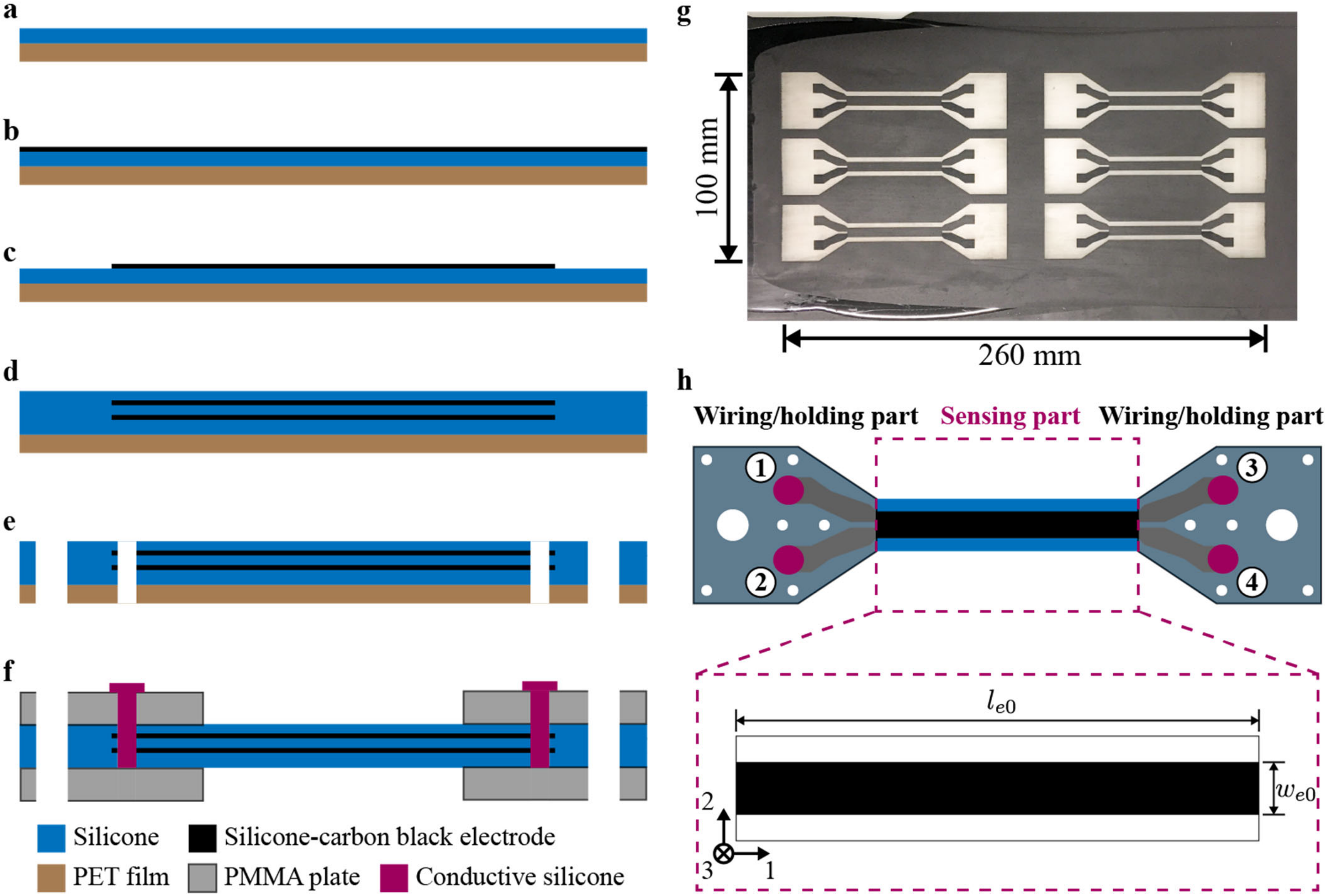
Capacitive sensing mode was more stable also for temperature and multiple cycles.

J. Shintake et al., *Adv. Mater. Technol.* **2017**, DOI: 10.1002/admt.201700284.


a
Sensor reading
Strain profile
$\Delta C/C_0$ [%]
Strain [%]
0
50
100
150
200
Time [sec]
0 100 200 300 400 500 600 700 800
b
Sensor reading
Strain profile
$\Delta R/R_0$ [%]
Strain [%]
0
50
100
150
200
0
75
150
225
300
Time [sec]
0 100 200 300 400 500 600 700 800
c
$\Delta C/C_0$ [%]
-50
0
50
100
150
200
250
$\varepsilon = 200$ %
$\varepsilon = 0$ %
Number of cycles
10^0 10^1 10^2 10^3 10^4 10^5
d
$\Delta R/R_0$ [%]
-70
0
70
140
210
280
350
$\varepsilon = 200$ %
$\varepsilon = 0$ %
Number of cycles
10^0 10^1 10^2 10^3 10^4 10^5


a
ΔC/C0 [%]
200
150
100
50
0
Strain [%]
0
50
100
150
200
1 mm/sec (2 %/sec)
10 mm/sec (20 %/sec)
25 mm/sec (50 %/sec)
b
ΔR/R0 [%]
350
300
250
200
150
100
50
0
Strain [%]
1 mm/sec (2 %/sec)
10 mm/sec (20 %/sec)
25 mm/sec (50 %/sec)
c
ΔC/C0 or ΔR/R0 [%]
2
0
-2
-4
-6
-8
-10
-12
-14
Temperature [°C]
20
30
40
50
60
70
80
Capacitive change
Resistive change


a
ΔC/C0 [%]
50
40
30
20
10
0
ΔR/R0 [%]
100
80
60
40
20
0
Strain [%]
0
10
20
30
40
50
Capacitive change
Resistive change
b
ΔC/C0 [%]
100
80
60
40
20
0
ΔR/R0 [%]
200
160
120
80
40
0
Strain [%]
0
20
40
60
80
100
Capacitive change
Resistive change
c
ΔC/C0 [%]
200
160
120
80
40
0
ΔR/R0 [%]
400
320
240
160
80
0
Strain [%]
0
50
100
150
200
Capacitive change
Resistive change
d
ΔC/C0 [%]
250
200
150
100
50
0
ΔR/R0 [%]
700
560
420
280
140
0
Strain [%]
0
50
100
150
200
250
300
Capacitive change
Resistive change
e
ΔC/C0 [%]
350
280
210
140
70
0
ΔR/R0 [%]
1200
960
720
480
240
0
Strain [%]
0
100
200
300
400
Capacitive change
Resistive change
f
ΔC/C0 [%]
450
360
270
180
90
0
ΔR/R0 [%]
1800
1440
1080
720
360
0
Strain [%]
0
100
200
300
400
500
Capacitive change
Resistive change


a
b
c
d
e
f
g
100 mm
260 mm
h
Wiring/holding part
Sensing part
Wiring/holding part
①
②
③
④
l_{e0}
w_{e0}
2
3
1
Silicone
Silicone-carbon black electrode
PET film
PMMA plate
Conductive silicone