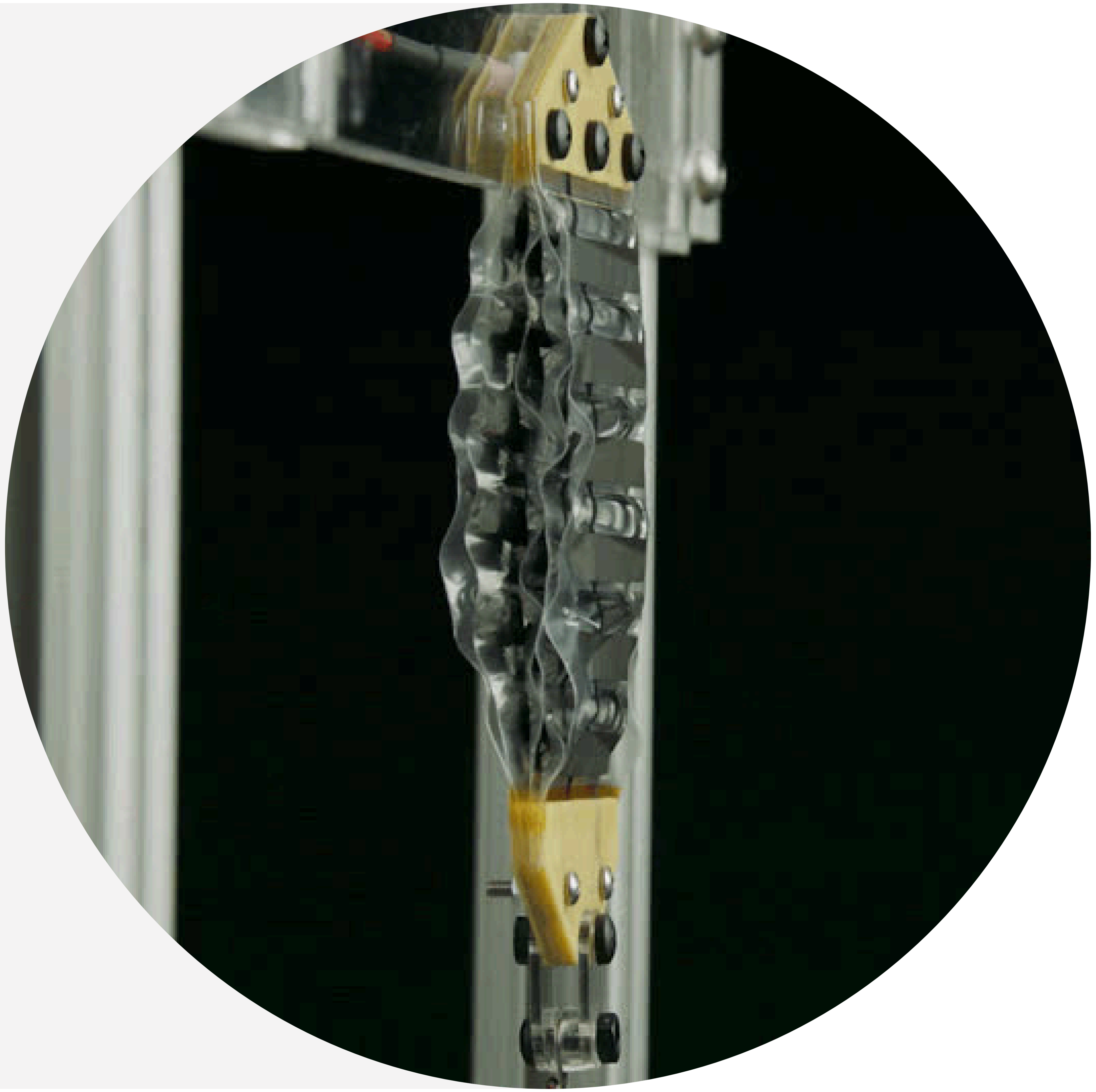
Firmin Chapoulie

HASEL ACTUATOR

HYDRAULICALLY AMPLIFIED SELF-HEALING ELECTROSTATIC

October 8th 2025



HASEL actuator

PROGRESS REPORT

ADVANCED MATERIALS
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HASEL Artificial Muscles for a New Generation of Lifelike Robots—Recent Progress and Future Opportunities

*Philipp Rothemund, Nicholas Kellaris, Shane K. Mitchell, Eric Acome, and Christoph Keplinger**

Future robots and intelligent systems will autonomously navigate in unstructured environments and closely collaborate with humans; integrated with our bodies and minds, they will allow us to surpass our physical limitations. Traditional robots are mostly built from rigid, metallic components and electromagnetic motors, which make them heavy, expensive, unsafe near people, and ill-suited for unpredictable environments. By contrast, biological organisms make extensive use of soft materials and radically outperform robots in terms of dexterity, agility, and adaptability. Particularly, natural muscle—a masterpiece of evolution—has long inspired researchers to create "artificial muscles" in an attempt to replicate its versatility, seamless integration with sensing, and ability to self-heal. To date, natural muscle remains unmatched in all-round performance, but rapid advancements in soft robotics have brought viable alternatives closer than ever. Herein, the recent development of hydraulically amplified self-healing electrostatic (HASEL) actuators, a new class of high-performance, self-sensing artificial muscles that couple electrostatic and hydraulic forces to achieve diverse modes of actuation, is discussed; current designs match or exceed natural muscle in many metrics. Research on materials, designs, fabrication, modeling, and control systems for HASEL actuators is detailed. In each area, research opportunities are identified, which together lays out a roadmap for actuators with drastically improved performance. With their unique versatility and wide potential for further improvement, HASEL actuators are poised to play an important role in a paradigm shift that fundamentally challenges the current limitations of robotic hardware toward future intelligent systems that replicate the vast capabilities of biological organisms.

1. Introduction

Popular culture is rife with examples of robotic assistants that increase our productivity and enhance our quality of life—from aiding humans in dangerous areas such as space exploration, to helping with mundane tasks around the home. This vision of robots that are integral to our daily lives is multifaceted. In part, it is driven by immediate needs, such as addressing the increasing labor shortages in industries such as agriculture, where there are not enough people to harvest crops in time; in other areas, it is driven by the desire to surpass our physical limitations through the integration of humans and machines: wearable robotics or exoskeletons that surpass our innate strength and endurance, or provide assistance to the elderly or those rehabilitating from injury. While robots today are impressive in their capabilities—especially in controlled environments such as an assembly line in a factory—they are often ill-suited in unstructured environments and can be dangerous for humans in collaborative situations. In order to realize a future in which robots can adapt to changing tasks and environments, we need machines that are extremely versatile in terms of their decision making and that are based on robotic hardware that can dynamically respond in a variety of situations.

In the last decades advances in robotics have been driven predominantly by increases in computing power, new sensing concepts and control algorithms, new machine learning approaches, and more generally artificial intelligence. Less focus has been placed on improving the body of robots, so they continue to rely on rigid, mostly metallic components and electromagnetic actuators such as servo and stepper motors. Ample inspiration for the search of new materials, actuation mechanisms, and sensors in robots can be found in nature. Using a variety of soft materials such as muscle and skin, nature has produced organisms that drastically outperform current robots in dexterity, agility, and adaptability. Especially inspirational is the natural muscle, which has evolved into an extremely versatile actuator. Natural muscle enables the rapid wing-flapping rates of a hummingbird, it is strong enough to move an

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DOI: 10.1002/adma.202003375

Adv. Mater. 2021, 33, 2003375 2003375 (1 of 28) © 2020 The Authors. Published by Wiley-VCH GmbH

CONTEXT

09 November 2020

University of Colorado, Boulder

- First prototype in 2018
- Report of the progress on the HASEL technology

CONTRIBUTIONS

- Soft robotic actuator
- Mammal-like performances

WHAT YOU WILL LEARN

01 WHAT IS SOFT ROBOTIC ?

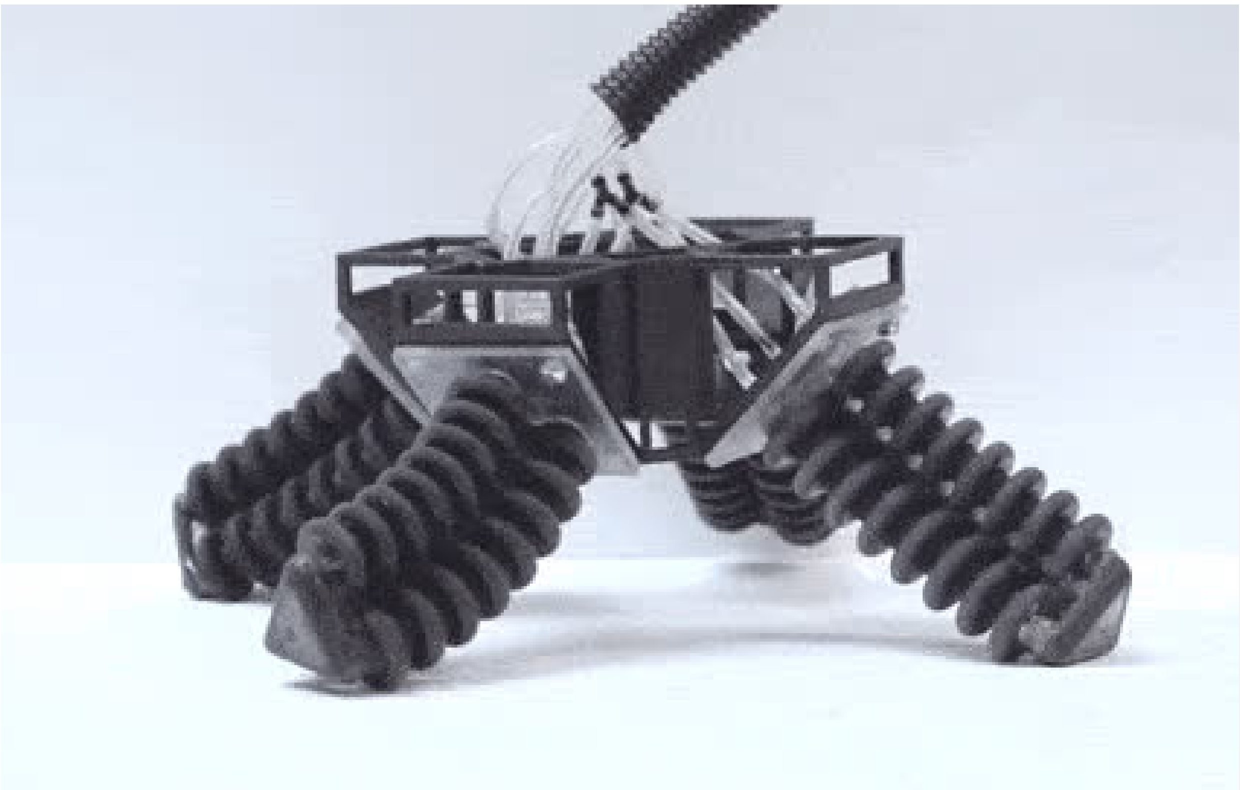
02 HASEL ACTUATORS

- PRINCIPAL
- BENEFITS
- PERFORMANCES

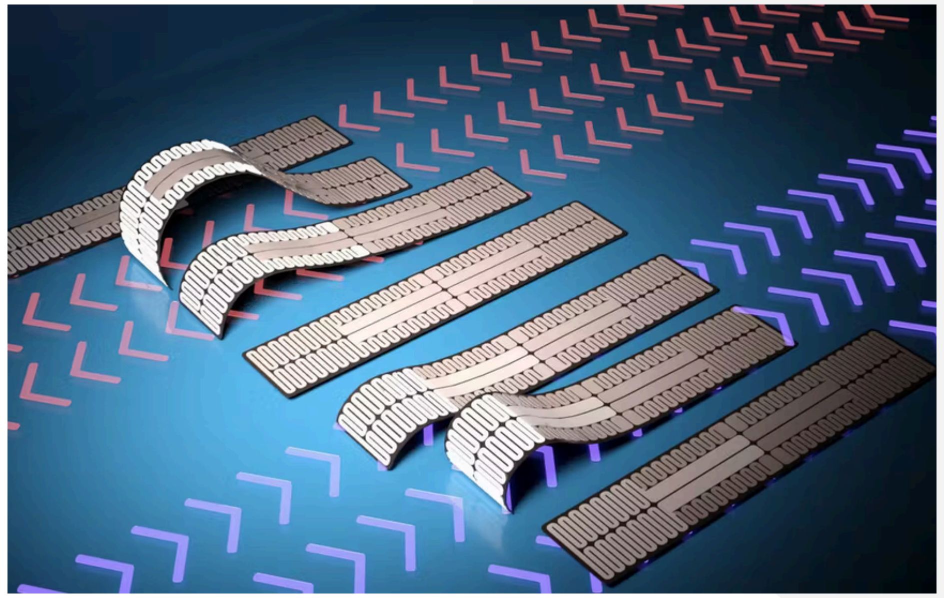
03 LIMITS

04 OUTLOOKS

SOFT ROBOTIC



Tolley (PneuNet)



caterpillarBot (heat)

Soft robotic is a field that involves robotic systems without rigid mechanisms, typically achieving actuation through bending and deformation.

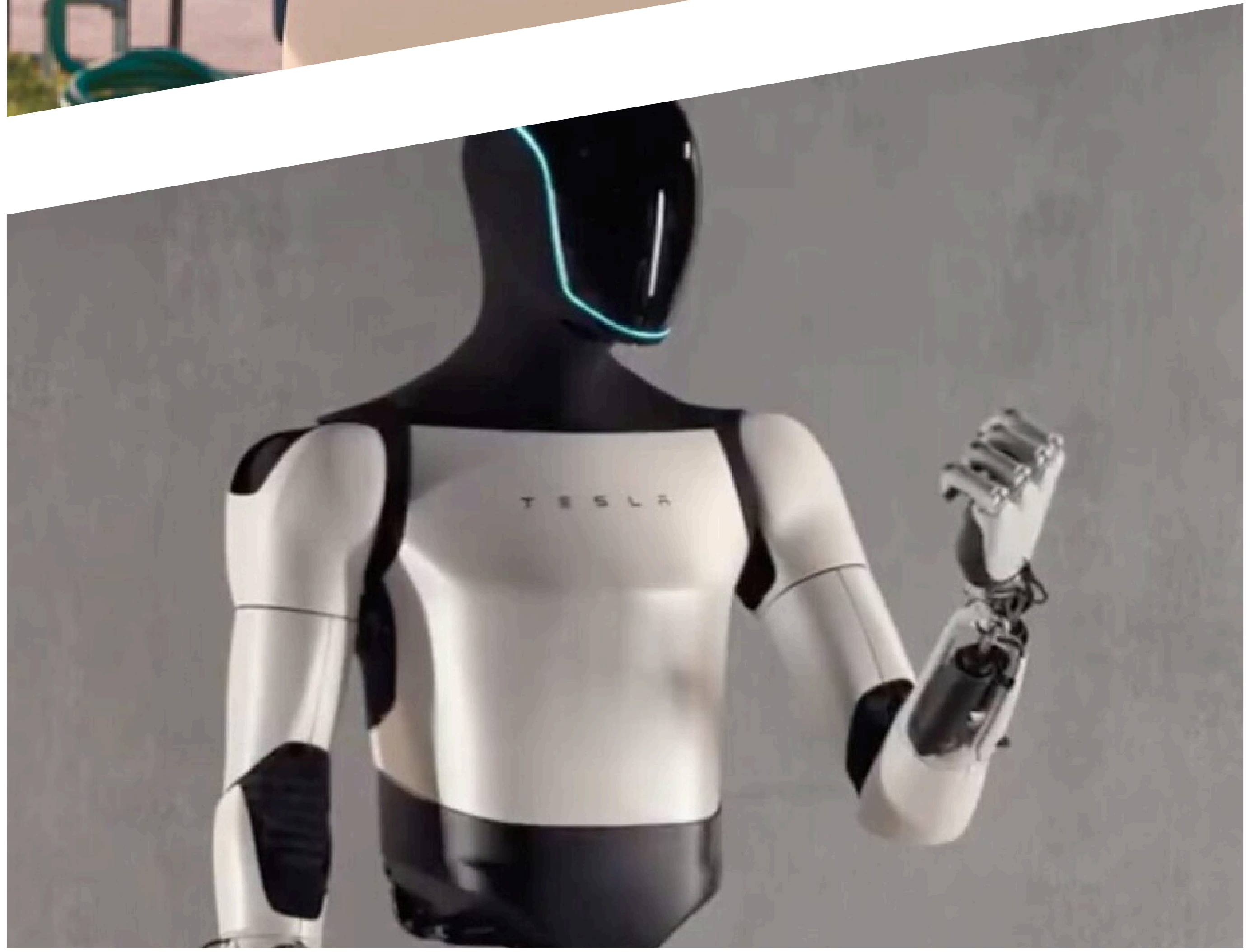
← Designs are usually bio-inspired
(ie : squid)

Start during the mid-1950s

Powered primarily by hydraulic or fluidic energy :

- Inability to achieve high-frequency actuation
- Higher operating costs due to reduced reliability

McKibben actuators



HASEL actuator

BENEFITS OVER RIGID SYSTEMS [1]

More adaptive / compliant with the environment

Reduce the risk/ improve security
- Cobotic
- Compatible for medical use

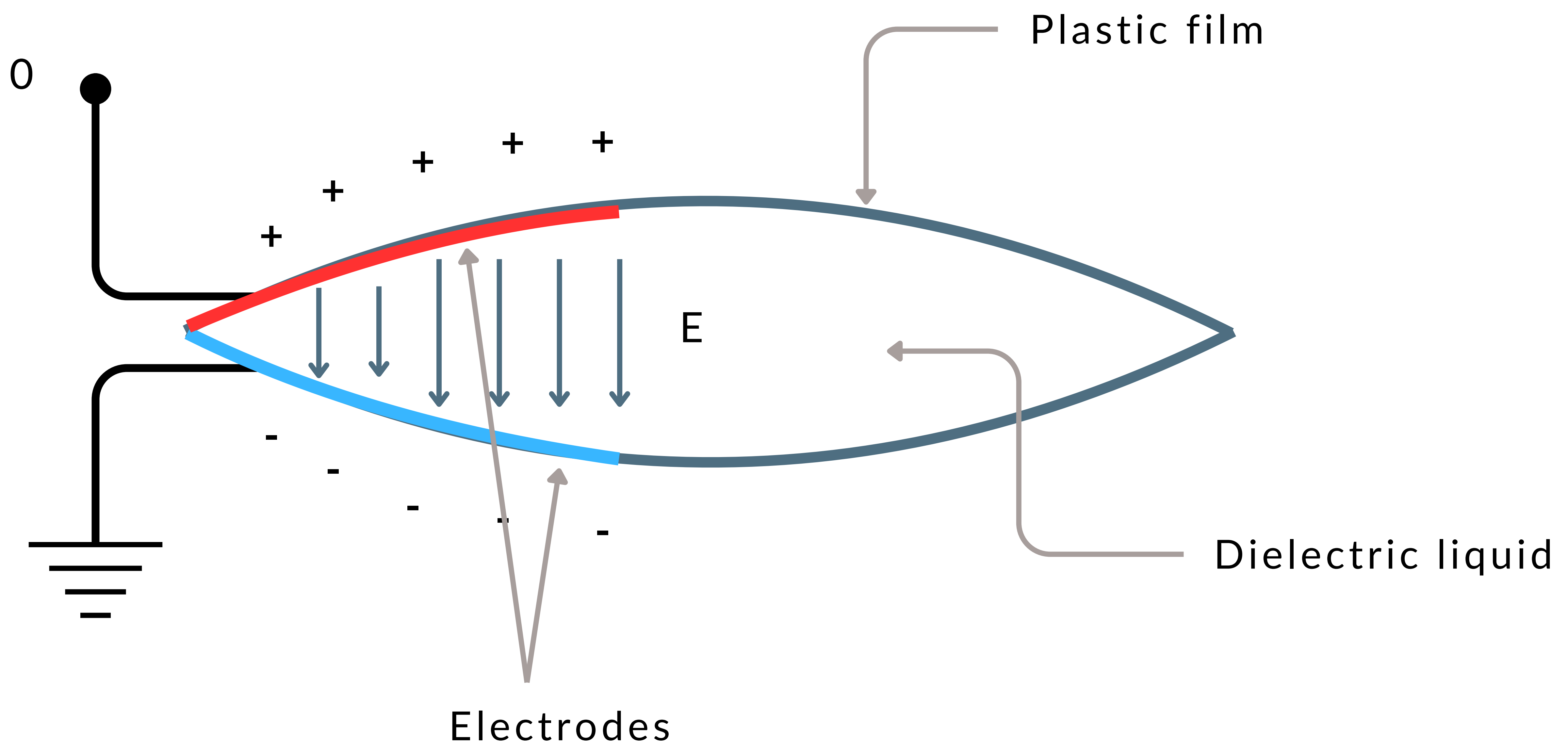
Allow bio-inspired design

Lighter than usual actuator and less resource consuming

Could improve the acceptance of robots

HASEL ACTUATOR PRINCIPAL

HASEL actuators use the Maxwell stress to deform the shell by moving the liquid.



PRINCIPAL

A voltage is applied to the actuator. Thus the resulting electric force tends to reduce the distance between the electrodes.

HASEL ACTUATOR PRINCIPAL

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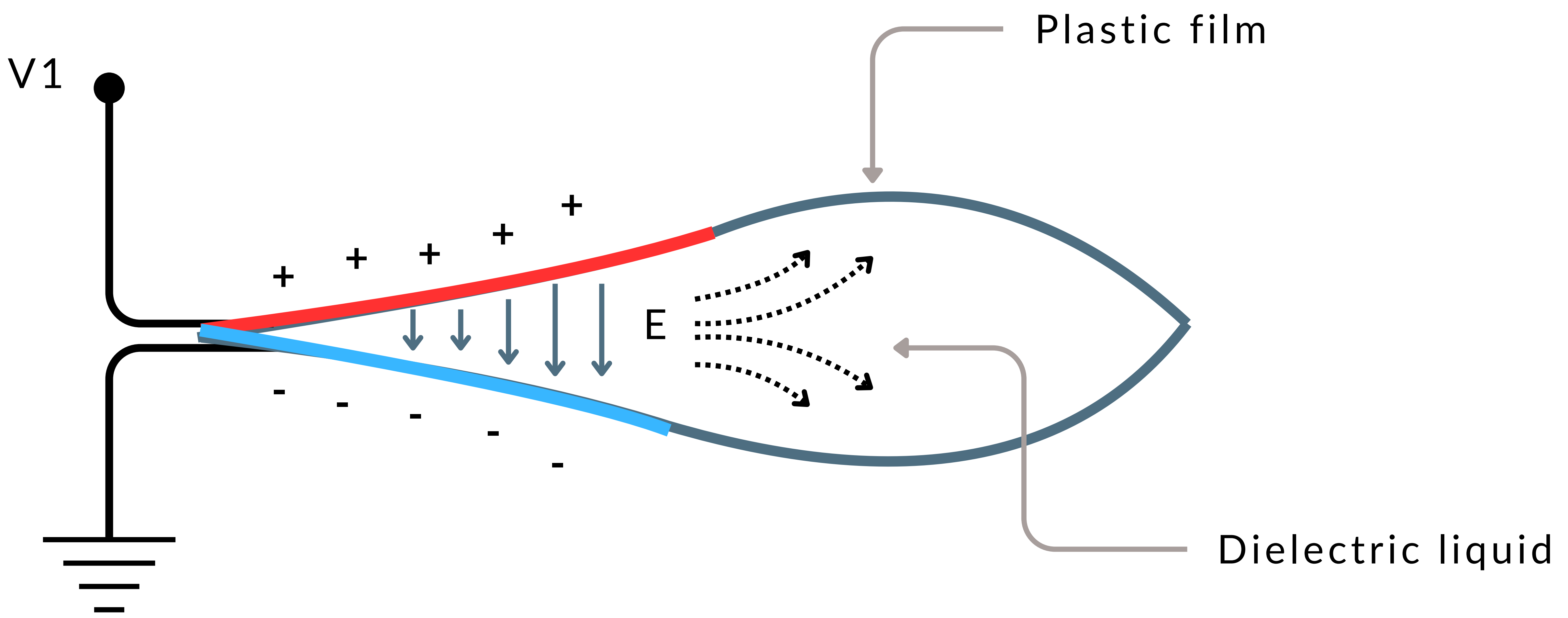
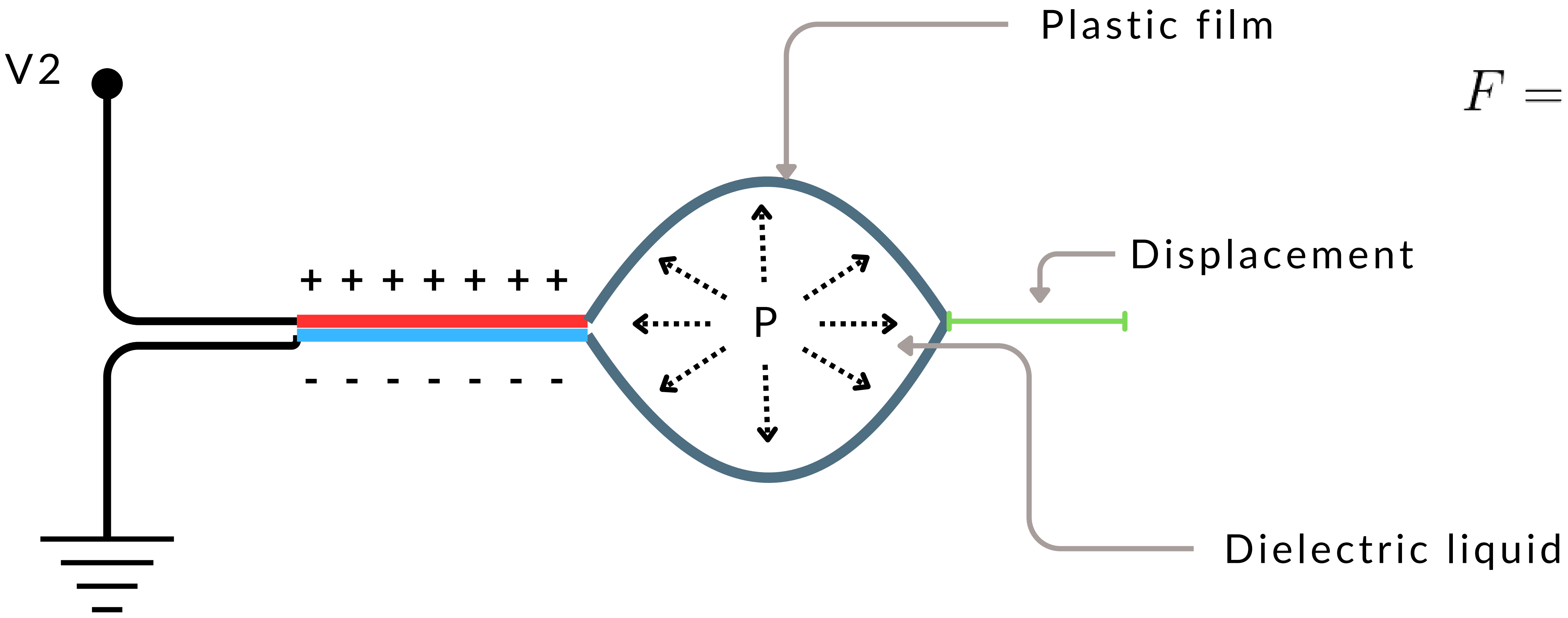


PRINCIPAL

The zipping movement displaces the liquid in the pouch, generating a deformation of the shell.

HASEL ACTUATOR PRINCIPAL

HASEL actuators use the Maxwell stress to deform the shell by moving the liquid.

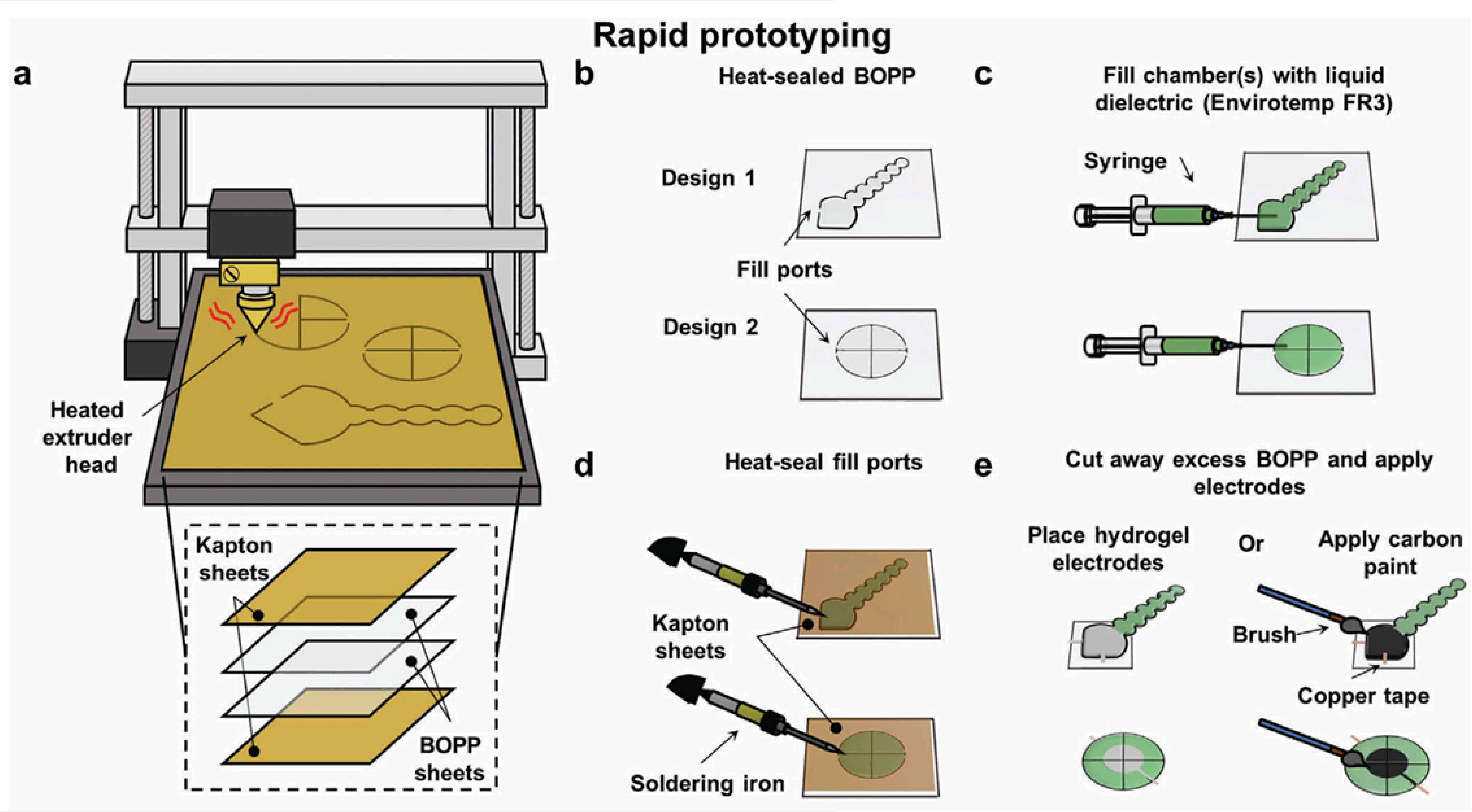


$$F = \frac{\varepsilon V^2}{t} \frac{v}{L^2} \frac{\alpha^3 cos(\alpha)}{(\alpha - sin(\alpha)cos(\alpha))^2}$$

HEALING ABILITY

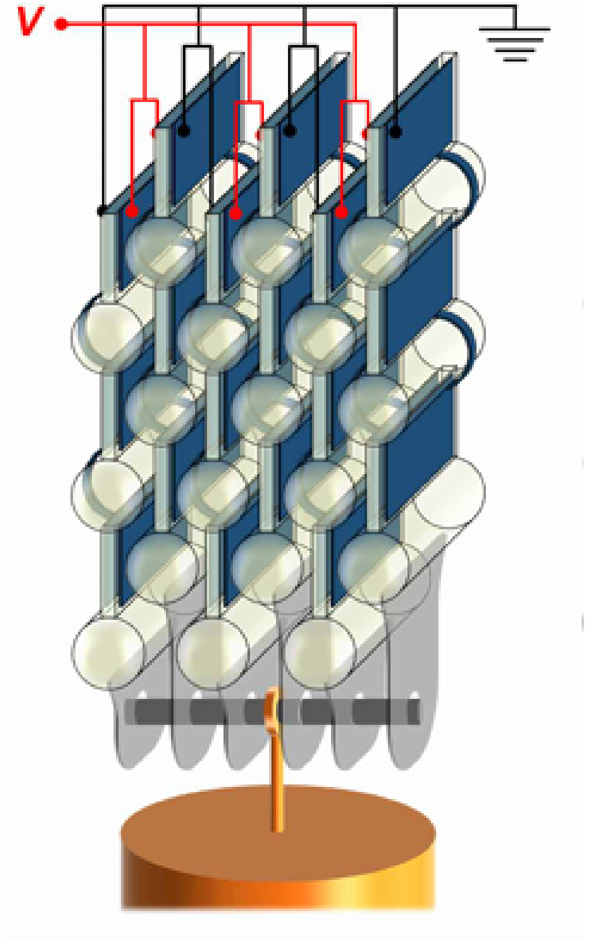
During an electrical breakdown, the dielectric liquid redistributes itself in the pouch and recovers its insulating state.

MANUFACTURING AN ACTUATOR



Prototyping of an HASEL actuator with a FDM printer

ENHANCING DESIGN



Like muscle fibers, we can stack HASEL pouches to improve overall strength [2]

MATERIAL DEPENDANCE

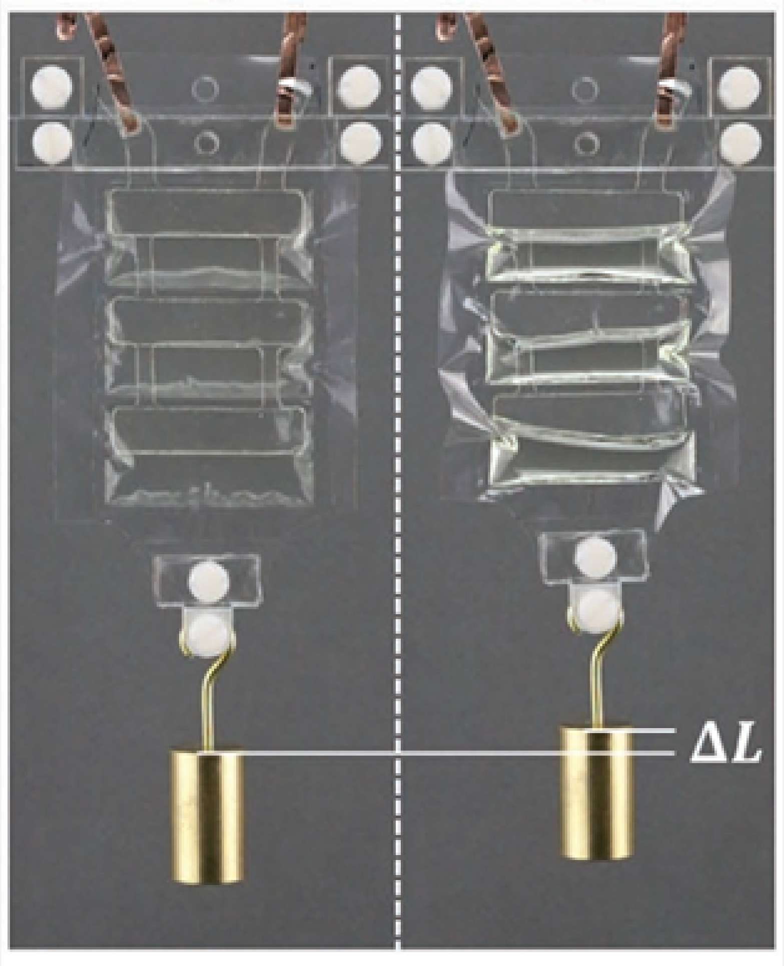
The material of the pouch changes the dynamic of the actuator as well as the viscosity of the dielectric liquid

PERFORMANCES UNDER LOAD CONSTRAINT

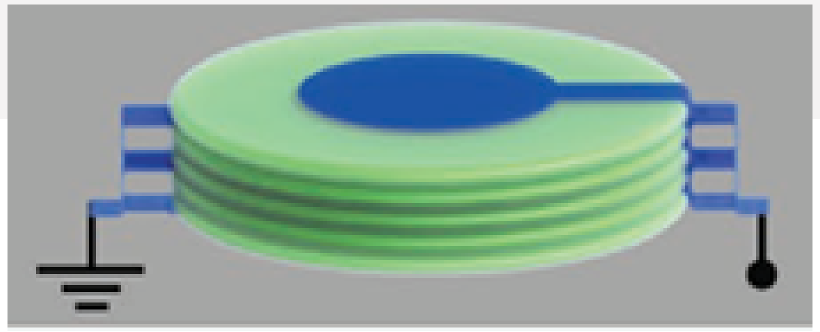
HASEL actuator

	Linear strain [%]	Max. actuation stress [MPa]	Peak strain rate [% s^{-1}]	Efficiency [%][a)]	Bandwidth [Hz][b)]	Lifetime [cycles]
Mammalian skeletal muscle	20 (typ) 40 (max)[3]	0.35[3]	500[3]	40[3]	Moderate[16]	10^9[4]
Elastomeric HASEL actuators						
Donut HASEL actuator	50[14]	0.002[c)]	–	21[14]	–	$>10^6$[14]
Planar HASEL actuator	124[d)][14]	0.3[d)][14]	–	–	–	10^5[14]
Thermoplastic HASEL actuators						
Peano-HASEL	15[96]	0.21[e)]	6100[97]	–	50[15]	10^4[15] to 10^5[f)]
HS-Peano-HASEL	24[97]	0.09[g)]	2200[97]	–	40[97]	–
Quadrant donut HASEL	118[89]	0.03[h)]	7400[89]	19[89]	126[89]	10^4[89] to 10^5[f)]

Comparison of current actuator performance for different types of HASEL actuators and mammalian skeletal muscle



Test bench

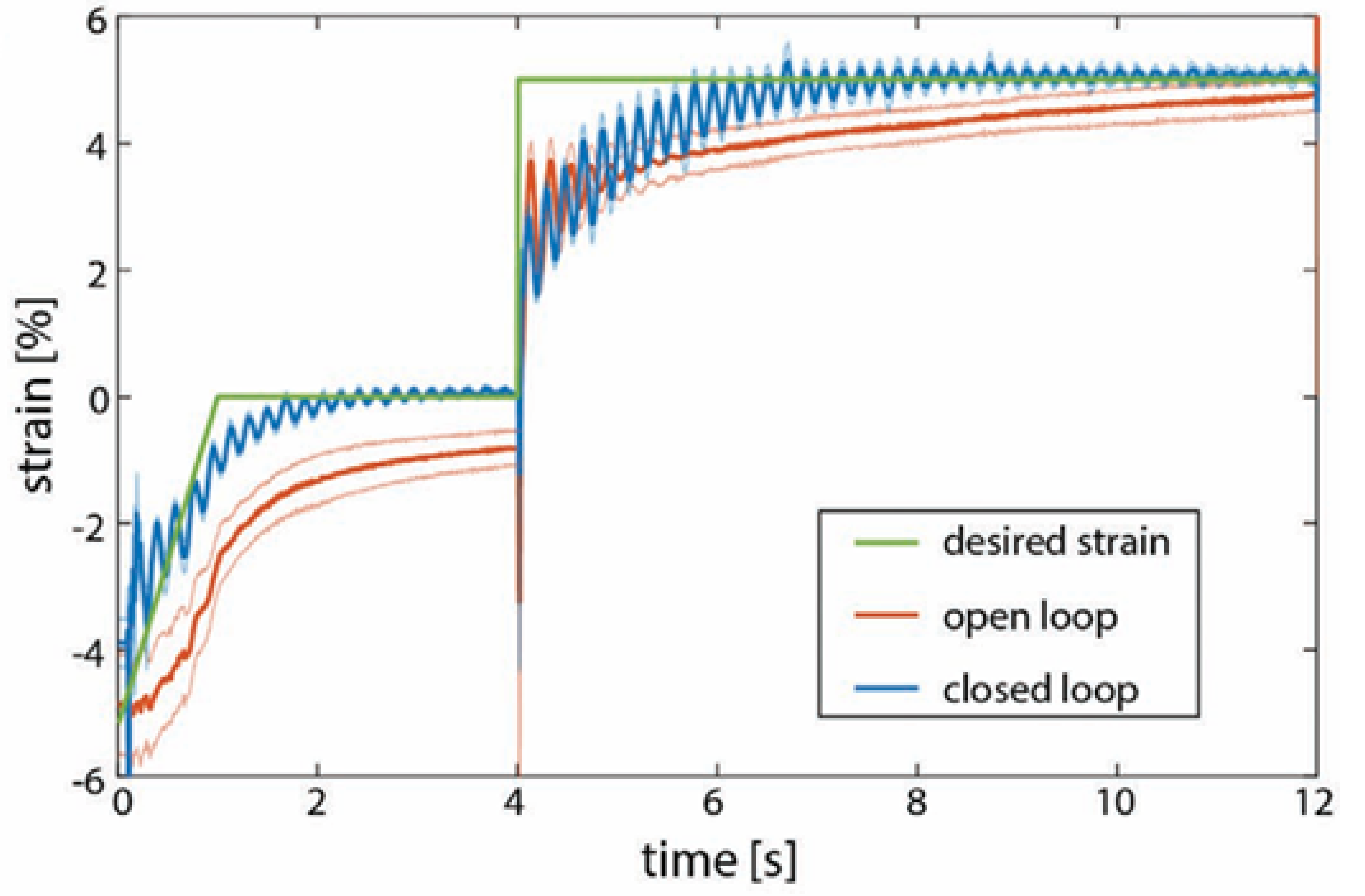


Donnut Hassel actuator

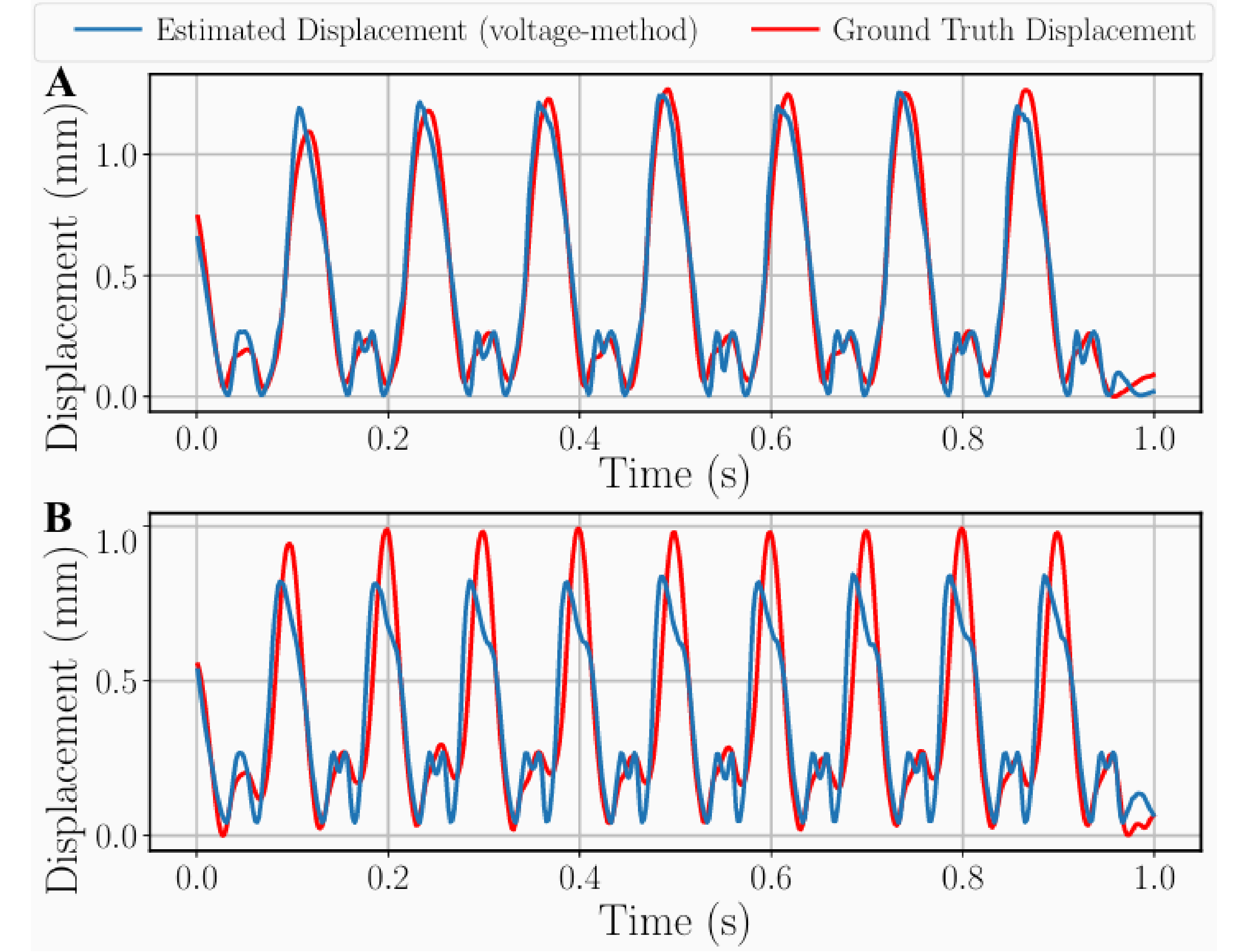
AUTOSENSING

Magnitude of the complex impedance :

$$|Z| = \sqrt{R_E^2 + \frac{1}{2\pi f^2} \frac{1}{C_E^2}}$$



Closed-loop control of a planar HASEL actuator for displacement con trol using self-sensing to measure deformation



Displacement estimation using the voltage-method of a sinusoidal actuation with amplitude 1kV and offset 3.5kV at (A) 8Hz and (B) 10Hz.

LIMITES

This technology can't compete against actual mechanical high-end robot systems

	Original finger design, DC motor	Original finger design, BOPP Peano-HASELs	Custom finger design, Mylar Peano-HASELs
Actuator weight (g)	37.0	43.6	38.8
Length × width × depth (cm)	5 × 2 × 1.5	15.5 × 5.4 × 0.65	16 × 7 × 0.64
Volume (cm^3)	15	54.4	71.7
Range of motion (deg)	85	29.7	77.17
Force at 30° (N)	13	0	0.91 (1.33)
Energy consumed to grasp (mJ)	3,800	311.4	437.5
Average power consumption during grasp (mW)	9,200*	5.6	0.94
Flexion speed (deg/s)	150	738	1,587
Bandwidth (Hz)	0.75	15.9	8.34
Flexion magnitude at 10 Hz (deg)	5.0	25.4	34.1

Summary of collected data comparing the original finger design actuated by both the DC motor and BOPP Peano-HASELs with the custom finger actuated by Mylar Peano-HASELs [3]

LIMITES

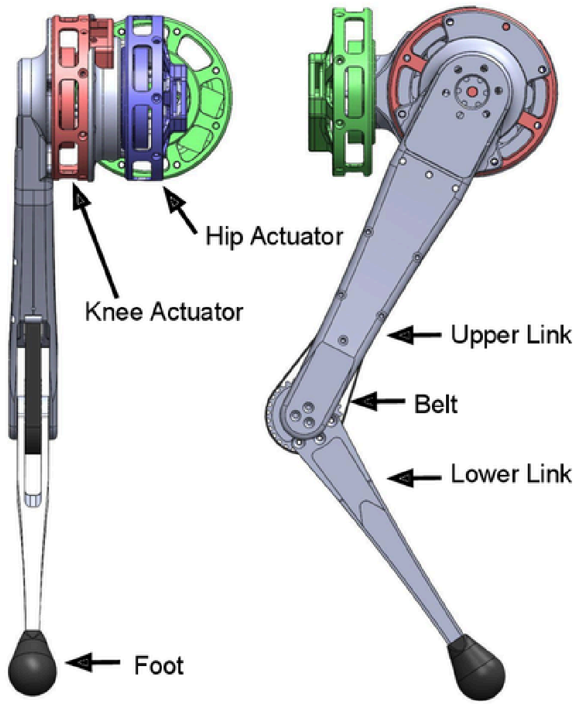
This technology can't compete against actual mechanical high-end robot systems

FOR DISPLACMENT

Bio-inspiration doesn't allow efficient strategies to move, such as crawling or mammalian techniques.

CAN'T REPLACE RIGID ROBOTIC

We can't just swap classic mechanisms with soft ones

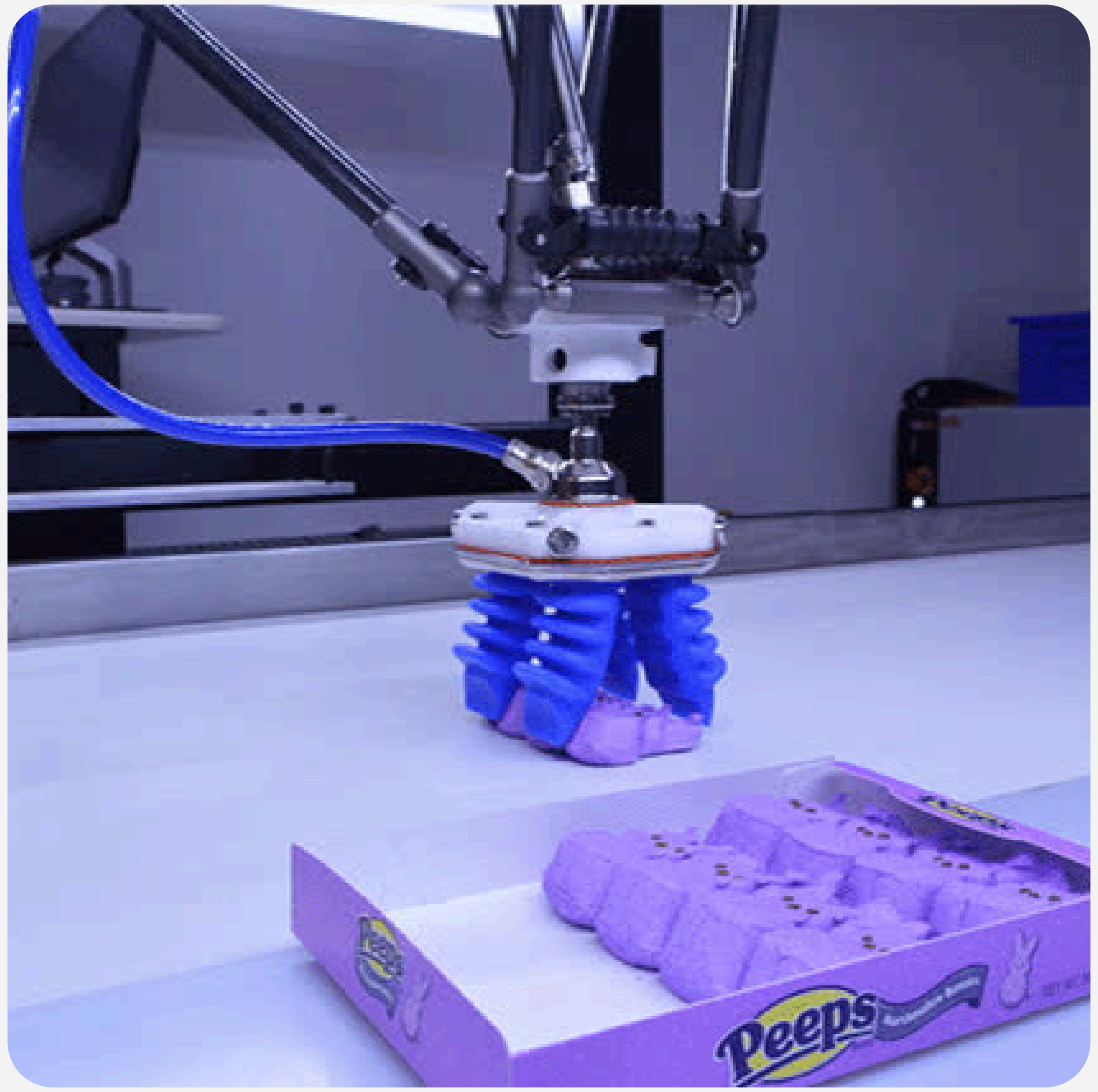


LACK OF INDUSTRIAL INTEREST

Few industrial applications exist, and there is only one supplier of HASEL actuators worldwide

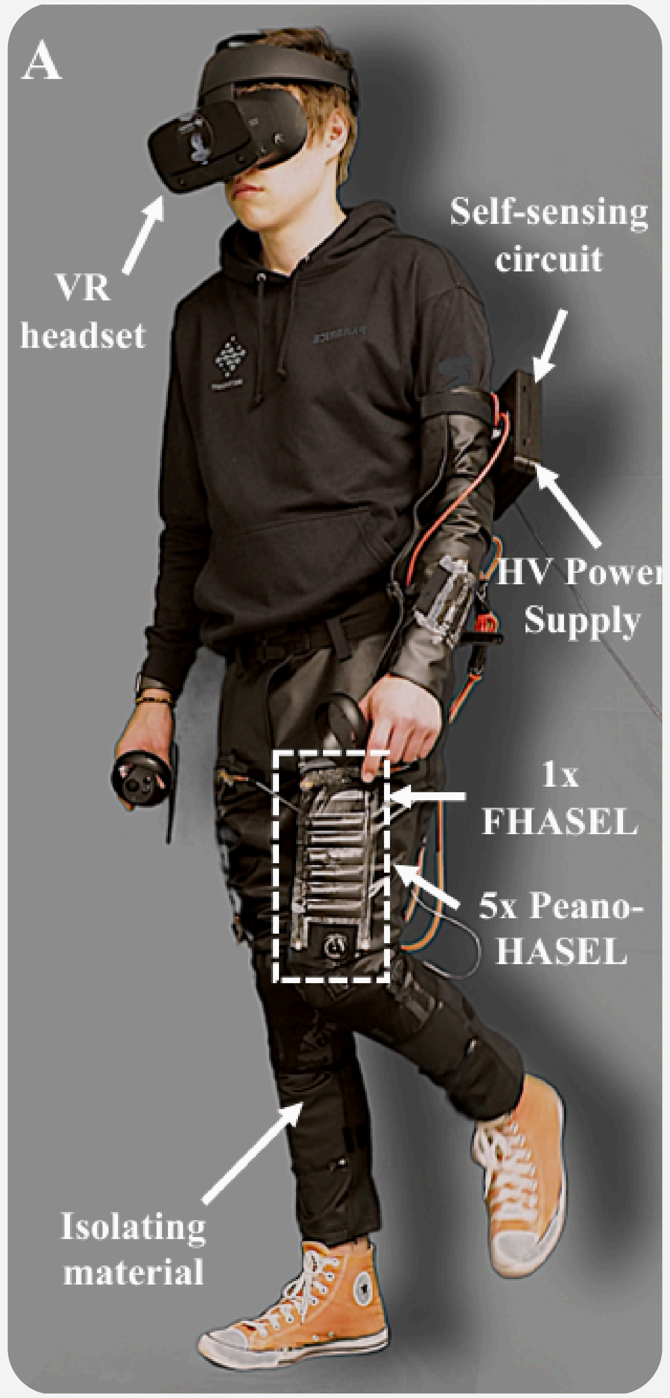
OUTLOOKS

Sensitive tasks



high sensitive gripper
for pick in place

Medical



Knee & hips tracker [4]

Bio-inspirations

Simulate
primitive life

HASEL actuator

THANK YOU

Your questions are welcome

SOURCES

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