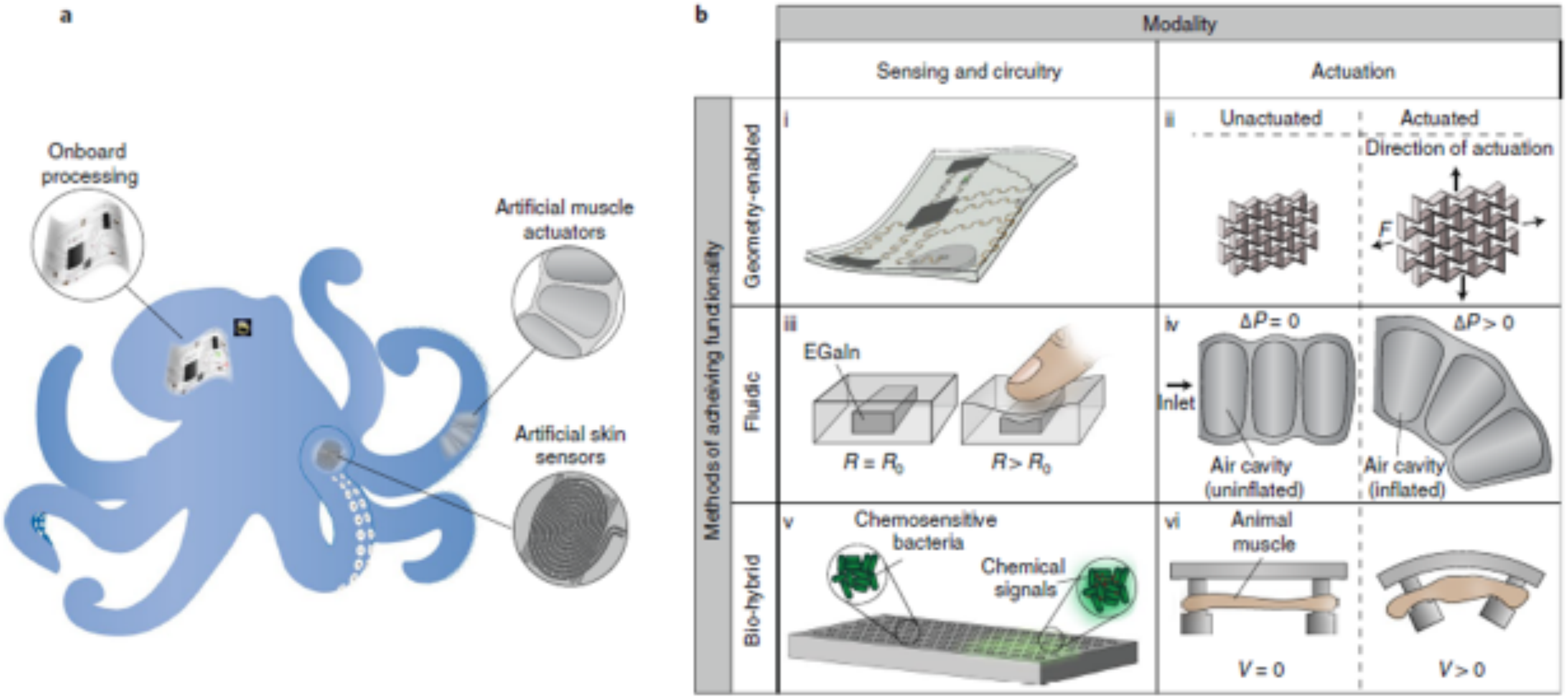
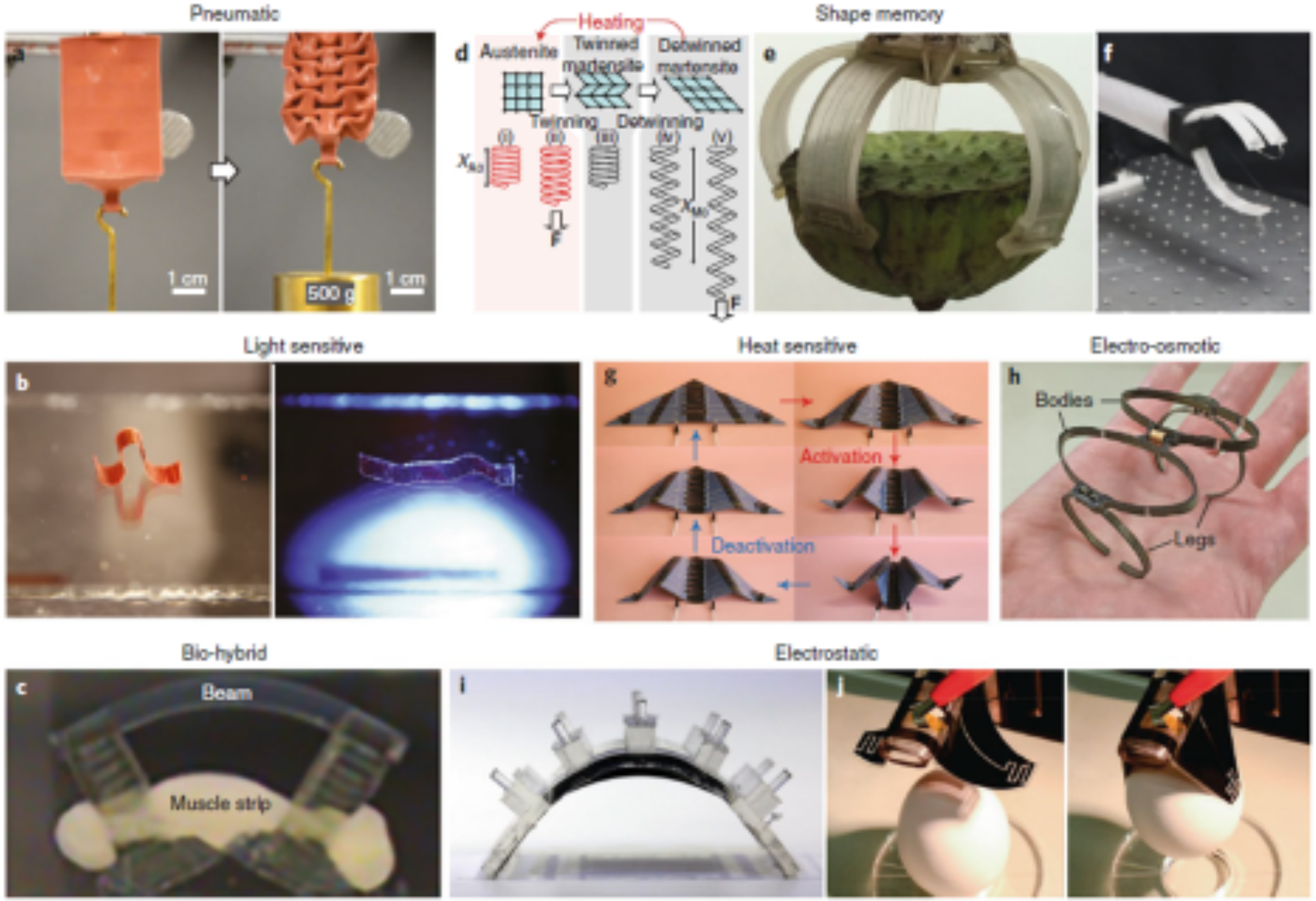
Introduction

- This presentation is the last in the sequence of Soft Robotics presentations, hence I will try to give a more overview what is happening in this space in the world labs/universities.
- The area of Soft Robotics has been alive since the beginning of 2000.
- As far as I know, the most active labs/Univ. are at Harvard, MIT (in Boston area) CMU and UPENN in Pennsylvania, Stanford, UC San Diego in California, Pisa in Italy, ETH in Switzerland.
- While many papers concentrate on one or the other aspect of the soft robot, all the lab/univ. must consider the following components:
- Material properties (continuous mechanics), fabrication, energizing (compressed air,hydrolic, temperature , magnetic,etc) sensing, control and interaction with the environment.


a
Onboard processing
Artificial muscle actuators
Artificial skin sensors
b
Modality
Sensing and circuitry
Actuation
Methods of acheiving functionality
Geometry-enabled
Fluidic
Bio-hybrid
i
ii
Unactuated
Actuated
Direction of actuation
F
iii
EGaIn
$R = R_0$
$R > R_0$
iv
$\Delta P = 0$
$\Delta P > 0$
Inlet
Air cavity (uninflated)
Air cavity (inflated)
v
Chemosensitive bacteria
Chemical signals
vi
Animal muscle
$V = 0$
$V > 0$

Soft Actuation using different energies ,pictures on the next slide

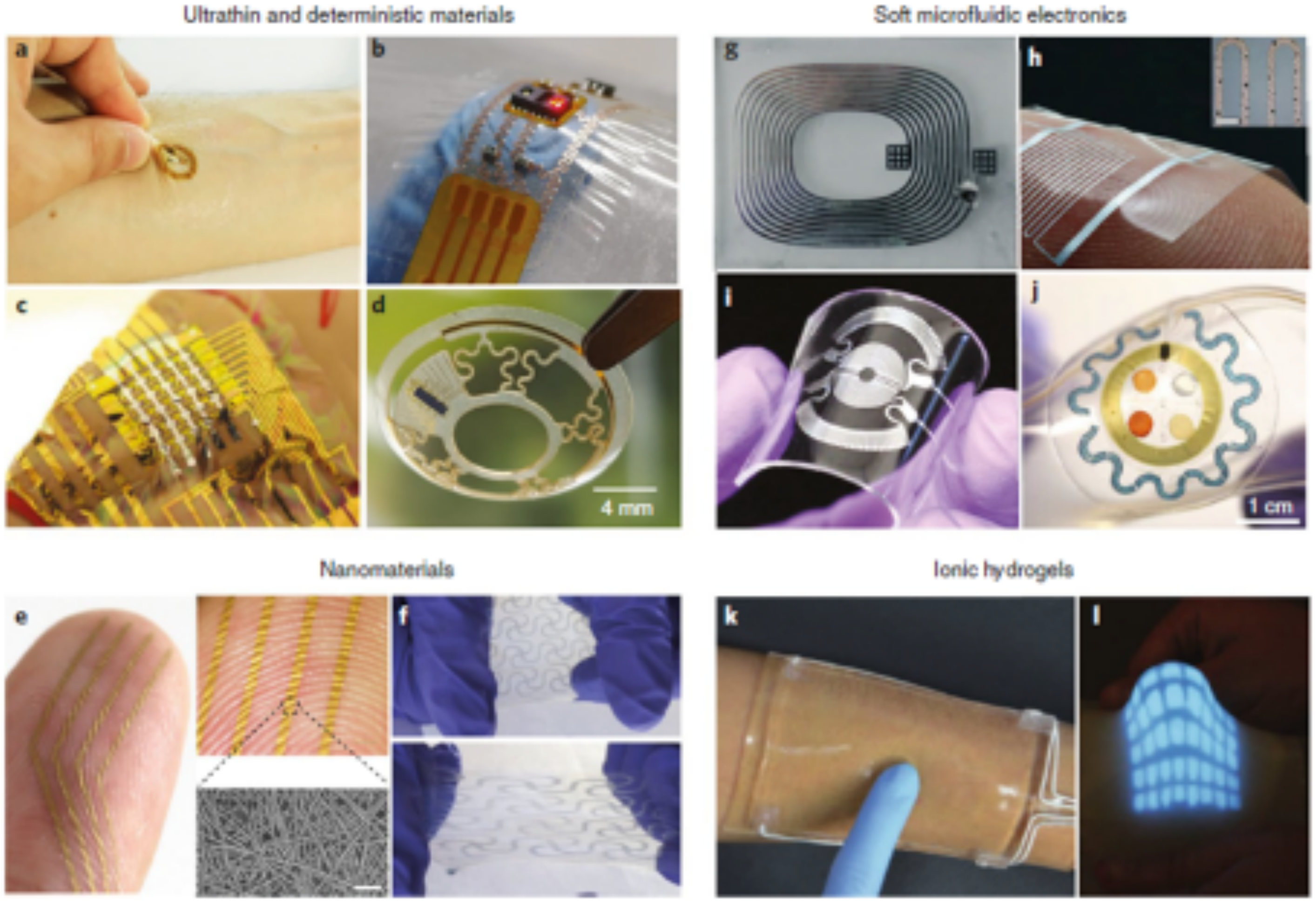
Fig. 2 | Methods of soft actuation. a, Vacuum-powered pneumatic actuator that creates contractile motion. **b**, A miniature LCE crawler (13 mm long) that moves in response to light. **c**, Bio-hybrid actuator (~4.6 mm long) with locomotion driven by electrically stimulated contraction of skeletal muscle. **d**, SMA spring, which contracts in response to resistive heating. In the diagram, **F** represents an applied force, while X_{A0} and X_{M0} represent the free length in the austenitic and martensitic spring, respectively. **e**, Modular gripper and walking robot actuated by resistive heating in an SMA. **f**, Gripper (100 mm long) actuated by resistive heating in a SMA. **g**, 3D-printed origami robot (110 mm side length) actuated by resistive heating in LCE hinges. **h**, Ionic polymer-metal composite-actuated caterpillar-inspired pipe crawling robot. **i**, Entirely soft, DEA-powered crawling robot (90 mm arc length). **j**, Dielectric elastomer actuator gripper, with increased gripping strength resulting from electrostatic adhesion. Credit: reproduced from ref. [28], Wiley (**a**); ref. [36], Wiley (**b**); ref. [17], National Academy of Sciences (**c**); ref. [51], IEEE (**d**); ref. [52], IOP (**e**); ref. [56], Elsevier (**f**); ref. [59], Royal Society of Chemistry (**g**); ref. [61], IEEE (**h**); ref. [67], SPIE (**i**); ref. [70], Wiley (**j**).



Pneumatic
a
1 cm
500 g
1 cm
d
Heating
Austenite
Twinned martensite
Detwinned martensite
Twinning
Detwinning
(i)
(ii)
(iii)
(iv)
(v)
F
F
Shape memory
e
f
Light sensitive
b
Heat sensitive
g
Activation
Deactivation
Electro-osmotic
h
Bodies
Legs
Bio-hybrid
c
Beam
Muscle strip
Electrostatic
i
j

Sensing used in soft robotics

Fig. 4 | Advances in soft sensing, conductivity and artificial skin. a–d, Sensors fabricated from ultrathin and deterministic architectures. **e**,**f**, Conductive soft structures achieved by structured nanomaterials. Scale bar in **e**, 5 µm. **g–j**, Conductive and wearable devices enabled by microfluidics. Scale bar in **h**, 5 mm. **k**,**l**, Wearable devices enabled by ionic hydrogel electronics. Specifically, these include: a mechano-acoustic on-skin sensor (**a**); a wearable device to measure electrophysiological signals and strain (**b**); an organic field-effect transistor/organic electrochemical transistor-enabled electrophysiology sensor array (**c**); a contact lens with integrated electronics (**d**); on-skin conductive traces that can measure strain and muscle activity (**e**); a highly stretchable PEDOT:PSS film applicable to transistor circuits (**f**); an EGaIn coil antenna fabricated by vacuum filling (**g**); a biphasic thin film of gold and gallium (**h**); a highly sensitive EGaIn-enabled pressure sensor (**i**); a colourimetric wearable patch for sweat analysis (**j**); a soft touch panel made from ionic hydrogels (**k**); and a stretchable LED array composed of 4 mm × 4 mm pixels, created from hydrogel and ZnS-doped dielectric elastomer (**l**). Credit: reproduced from ref. [74], AAAS (**a**); ref. [75], Wiley (**b**); ref. [78], Wiley (**c**); ref. [80], Wiley (**d**); ref. [139], Macmillan Publishers Ltd (**e**); ref. [97], AAAS (**f**); ref. [104], Royal Society of Chemistry (**g**); ref. [105], Wiley (**h**); ref. [106], Wiley (**i**); ref. [112], AAAS (**j**); ref. [113], AAAS (**k**); ref. [7], AAAS (**l**).


Ultrathin and deterministic materials
Soft microfluidic electronics
a
b
c
d
4 mm
g
h
i
j
1 cm
Nanomaterials
Ionic hydrogels
e
f
k
l

Examples of robotic systems on the next slide

Fig. 1 | Overview of soft robotic systems. a, Conception of a future soft robot, inspired by current state-of-the-art octopus-inspired robots[5,6]. This figure envisages the ways in which soft robotic technologies could be implemented in an advanced soft robot. **b**, Example methods of achieving circuitry and actuation for each generalized strategy (geometry-enabled, fluidic and bio-hybrid): (i) serpentine or wavy copper wiring between IC components that allow stretching; (ii) deterministic design of an auxetic metamaterial to create actuation in the *y*-direction in response to a force (F) in the *x*-direction; (iii) microfluidic sensing enabled by the change in cross-sectional area of an EGaIn microchannel, which causes the resistance (R) to increase from its initial value (R_0); (iv) pneumatic actuation caused by the asymmetric expansion of air cavities under pressure, where ΔP is the difference between pressure in the cavity and external pressure; (v) bio-hybrid sensing enabled by the luminescence of phytobacteria in response to chemical signals; and (vi) bio-hybrid actuation demonstrated when muscle cells contract under an applied voltage V.

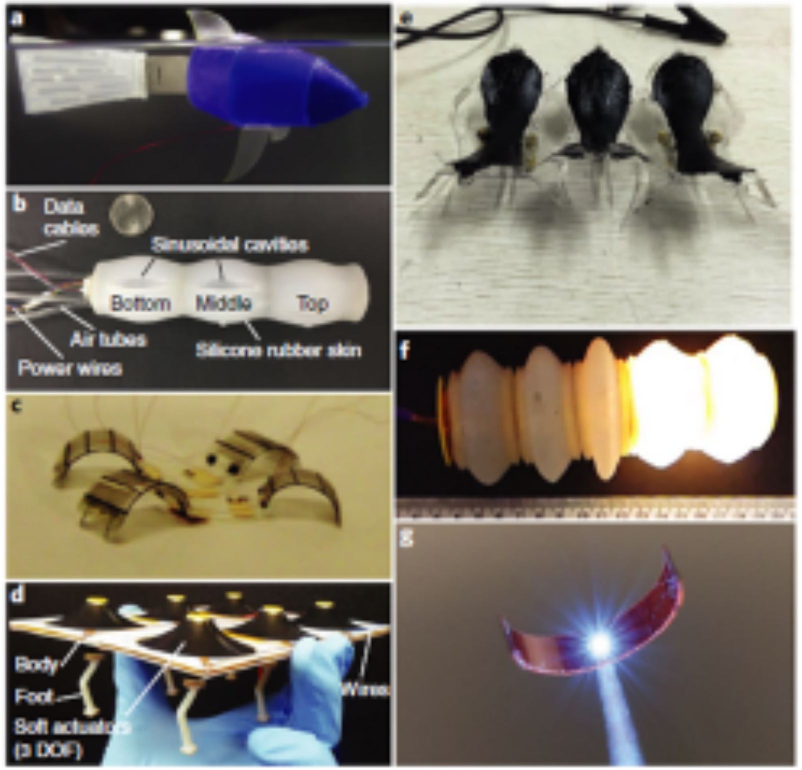
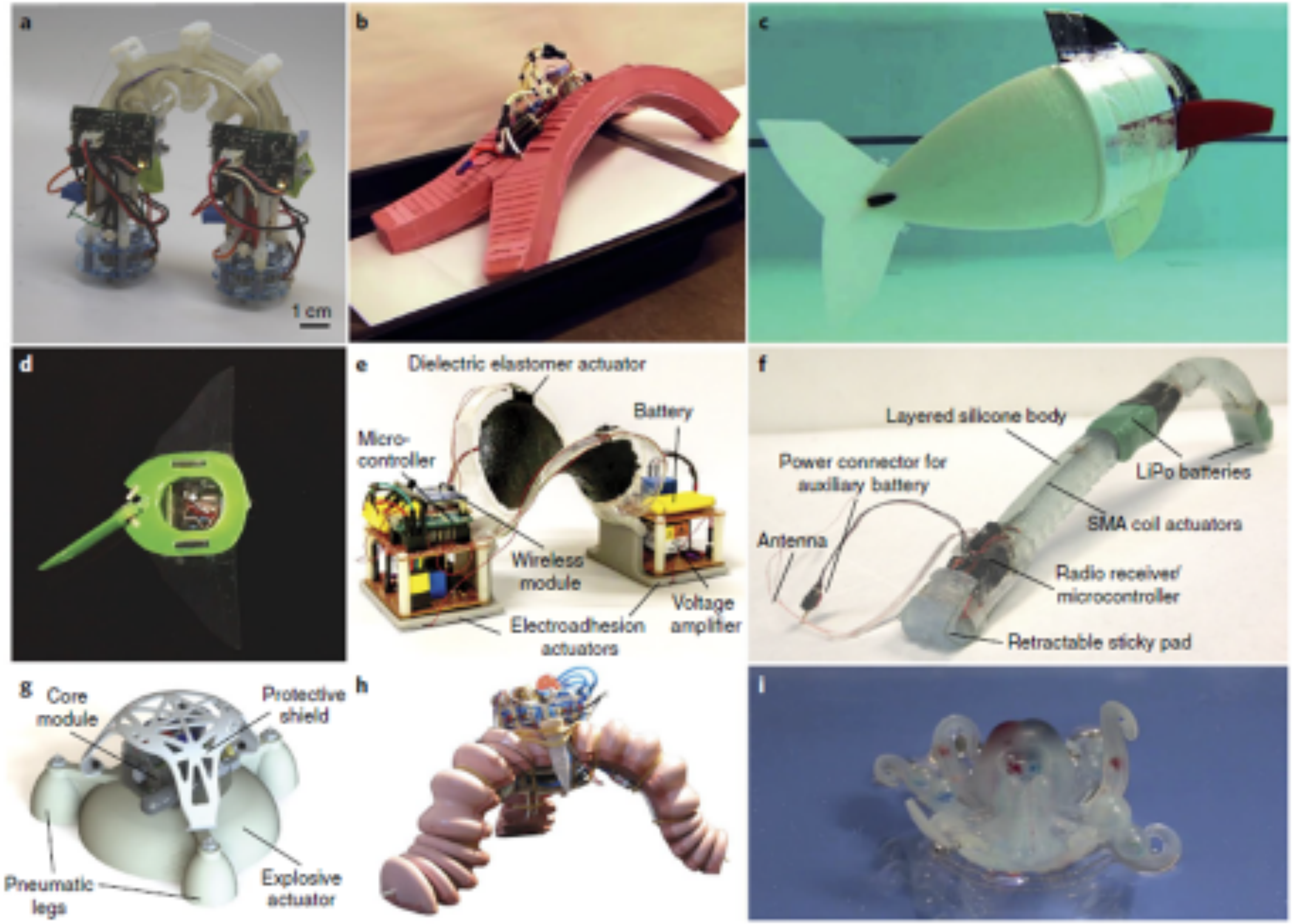


Fig. 5 | Implementation of soft actuators into robotic systems. a, SMA-actuated fish (20 cm long). **b**, SMA-actuated peristalsis robot (13.9 cm diameter). **c**, Fast DEA-actuated walker (6 cm). **d**, A multi-degree-of-freedom (DOF) DEA-powered walker. **e**, Differential friction, DEA-powered annelid robot (17 cm). **f**, Electromagnetically actuated pneumatic worm-robot. **g**, Venus flytrap-inspired, LCE-actuated gripper (5 mm). Credit: reproduced from ref. [55], National Academy of Sciences (**a**); ref. [54], IEEE (**b**); ref. [63], IEEE (**c**); ref. [68], Elsevier (**d**); ref. [117], IOP (**e**); ref. [32], Mary Ann Liebert (**f**); ref. [35], Macmillan Publishers Ltd (**g**).

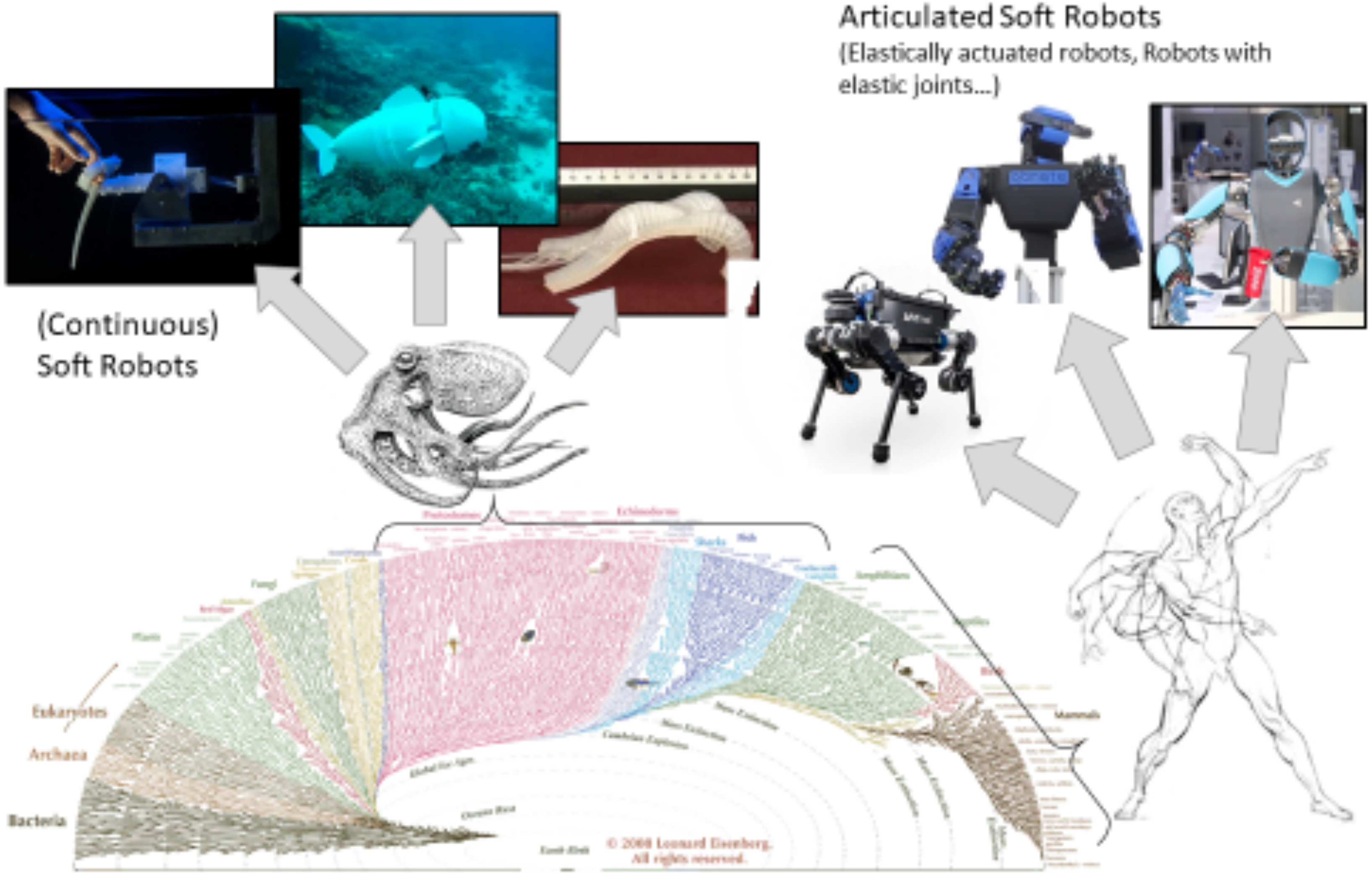
Soft robots delivering a mobility task

Fig. 6 | Fully untethered robotic systems. a, Climbing robot powered by a motor-cable system. **b**, Robust walking robot powered by on-board pneumatics (65 cm long). **c**, Biomimetic swimming robot powered by a hydraulic actuation system (35 cm long). **d**, Ray-inspired swimming robot powered by DEAs (9.3 cm long). **e**, Electro-adhesive walking robot powered by DEAs. (17 cm outer diameter) **f**, Caterpillar-inspired multi-gait robot powered by SMAs (10 cm long). **g**, Jumping robot powered by combustion (12.6 cm tall; 30 cm radius). **h**, Jumping robot with controllable orientation powered by combustion (8 cm tall; 15 cm radius). **i**, Octopus robot powered by combustion and controlled by fluidic logic (~55 mm). Credit: reproduced from ref. [118], IEEE (**a**); ref. [22], Mary Ann Liebert (**b**); ref. [119], Mary Ann Liebert (**c**); ref. [65], AAAS (**d**); ref. [123], SPIE (**e**); ref. [122], IOP (**f**); ref. [42], AAAS (**g**); ref. [31], IEEE (**h**); ref. [12], Macmillan Publishers Ltd (**i**).



a
1 cm
b
c
d
e
Dielectric elastomer actuator
Battery
Micro-
controller
Wireless
module
Electroadhesion
actuators
Voltage
amplifier
f
Layered silicone body
Power connector for
auxiliary battery
LiPo batteries
SMA coil actuators
Antenna
Radio receiver/
microcontroller
Retractable sticky pad
g
Core
module
Protective
shield
Pneumatic
legs
Explosive
actuator
h
i

Elastic bodies inspired by nature



Biological Motivation

- Growth as a method for navigating the environment is found in fungal hyphae with diameters as small as a few micrometers as well as in vines with girths as largeas a meter. These organisms grow from their tips, increase length hundreds of times ,and continually control growth direction based on environment stimuli. Because lengthening
- From the tip ,or apical extension, involves no relative movement of the body with respect to the environment , the body can lengthen along constrained path without friction from sliding against the environment. See the next slide in Fig 1A.

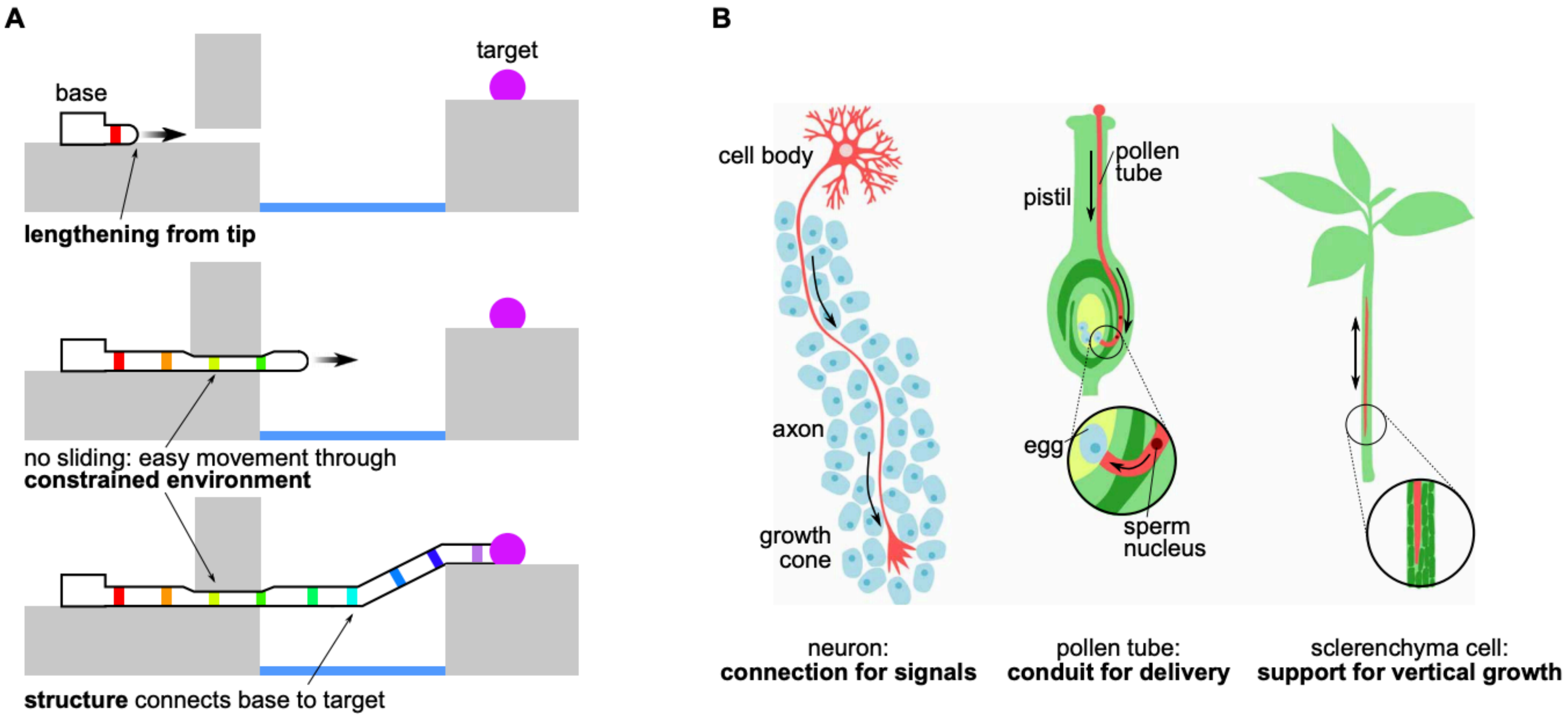


Fig. 1. Substantial lengthening from the tip with directional control enables a body to pass through a constrained environment and create a structure along its path of growth. (**A**) A body lengthens from its tip toward a target. Because only the tip moves, there is no relative movement of the body with respect to the environment (colored bands do not move). This results in the capability to move with no sliding friction through a constrained environment. As the tip moves, the body forms into a structure in the shape of the tip's path. (**B**) Examples of biological systems that grow to navigate their environments. Neurons grow through constrained tissue to create structures that act as signal pathways. Pollen tubes lengthen through pistil tissue to build conduits to deliver sperm to the ovary. Sclerenchyma cells grow within the xylem and phloem to create supporting structures.

Three dimensional structure of the body

- Along the path. These capabilities enable natural cells and organisms to grow through tightly packed tissue or abiotic materials and form structures with functions ranging from signal pathways to conduits for delivery, see Figure 1B.

Recreation of this behavior in artificial system

- Two principles :
- First ,an inverted ,compliant, thin-walled vessel will lengthen .
- from the tip by everting when pressurized.
- Second ,the tip of the vessel steers along the path when the relative lengths of the sides of the vessel are controlled while everting.
- See these principles the next slide.

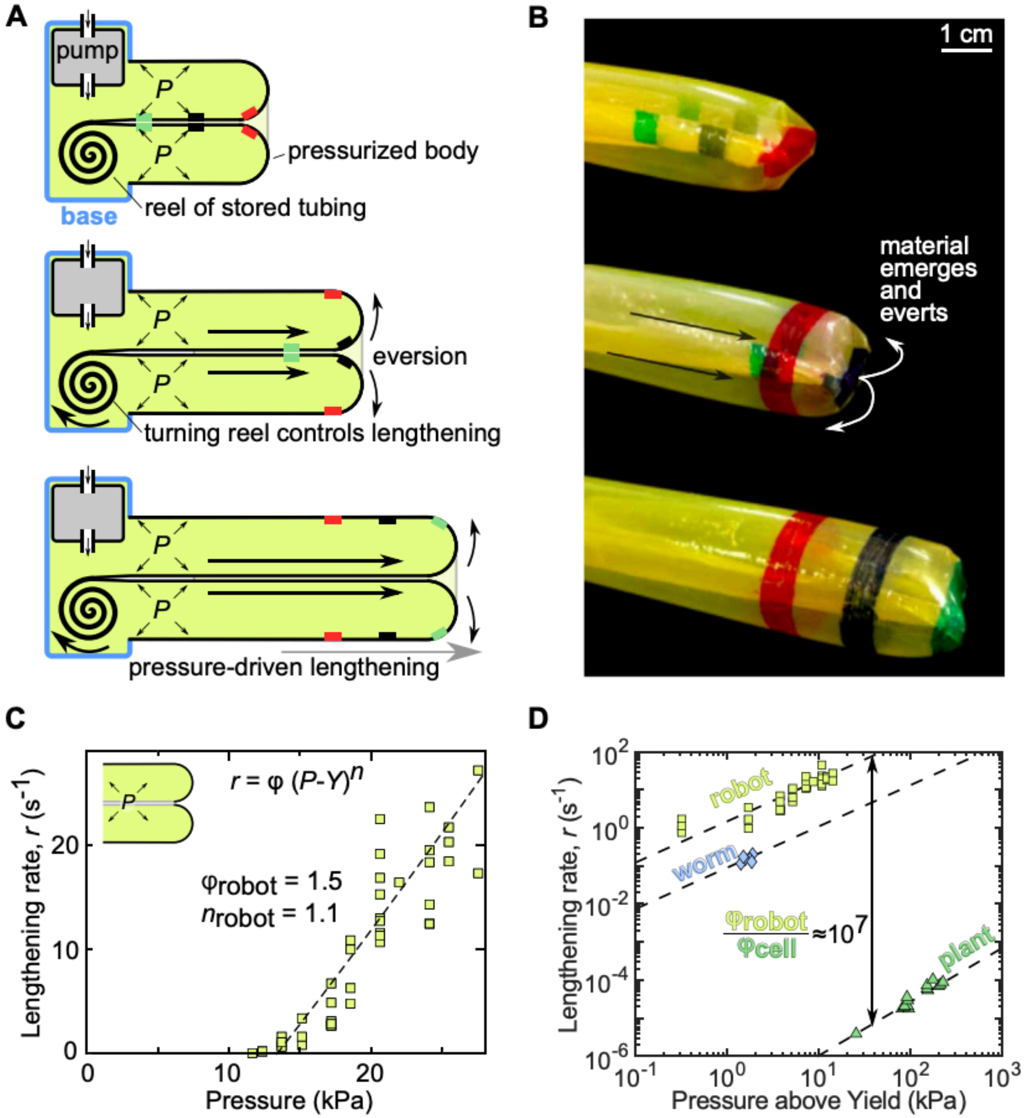


Fig. 2. Principle of pressure-driven eversion enables lengthening from the tip at rates much higher than those found in plant cell growth. (**A**) Implementation of principle in a soft robot. A pump pressurizes the body, which lengthens as the material everts at the tip. This material, which is compacted and stored on a reel in the base, passes through the core of the body to the tip; the rotation of the reel controls the length of the robot body. (**B**) Images of the lengthening body. The body diameter is 2.5 cm. (**C**) The relationship between lengthening rate (r) and internal pressure (P) shows a characteristic viscoplastic behavior: no extension below a yield pressure (Y) followed by a monotonic relationship between rate and pressure with a power term (n) close to 1. (**D**) Data show the relationship between rate and pressure above yield for the soft robot, worms with an everting proboscis (*S. nudus*), and a plant cell (*Nitella mucronata*). The extensibility φ (inverse viscosity) of a soft robot body is roughly seven orders of magnitude higher than that of the plant cell, resulting in a lengthening rate that is roughly five orders of magnitude higher. The extensibility of the soft robot body is slightly higher than the worm, which uses the same principle for lengthening.

The Principle of Asymetric Lengthening

- The principle of lengthening based on pressure-driven eversion also results in relatively fast lengthening especially when compared to organisms that use growth to navigate their environments, such as certain fungi and plants. To understand the behavior of the rate of lengthening in this system, they measured the rate as they varied the internal pressure. See the Figure below 3C. Because of the energy losses caused by everting the membrane, we see a behavior characteristic of a Bingham plastic, in which there is a minimum required pressure before yield , and a monotonic relationship between the rate of lengthening and pressure.

The second Principle

- The authors say is that they leverage form their design which enables the active control of directions and is based on setting the relative lengths of either side of the body at the tip as the body grows in length. There is the principle of directional control!!
- In their system, they implement this principle of selectivity, allowing one side of the body of the robot to length with respect to the other side as the body everts form the tip(Fig 3A to D).

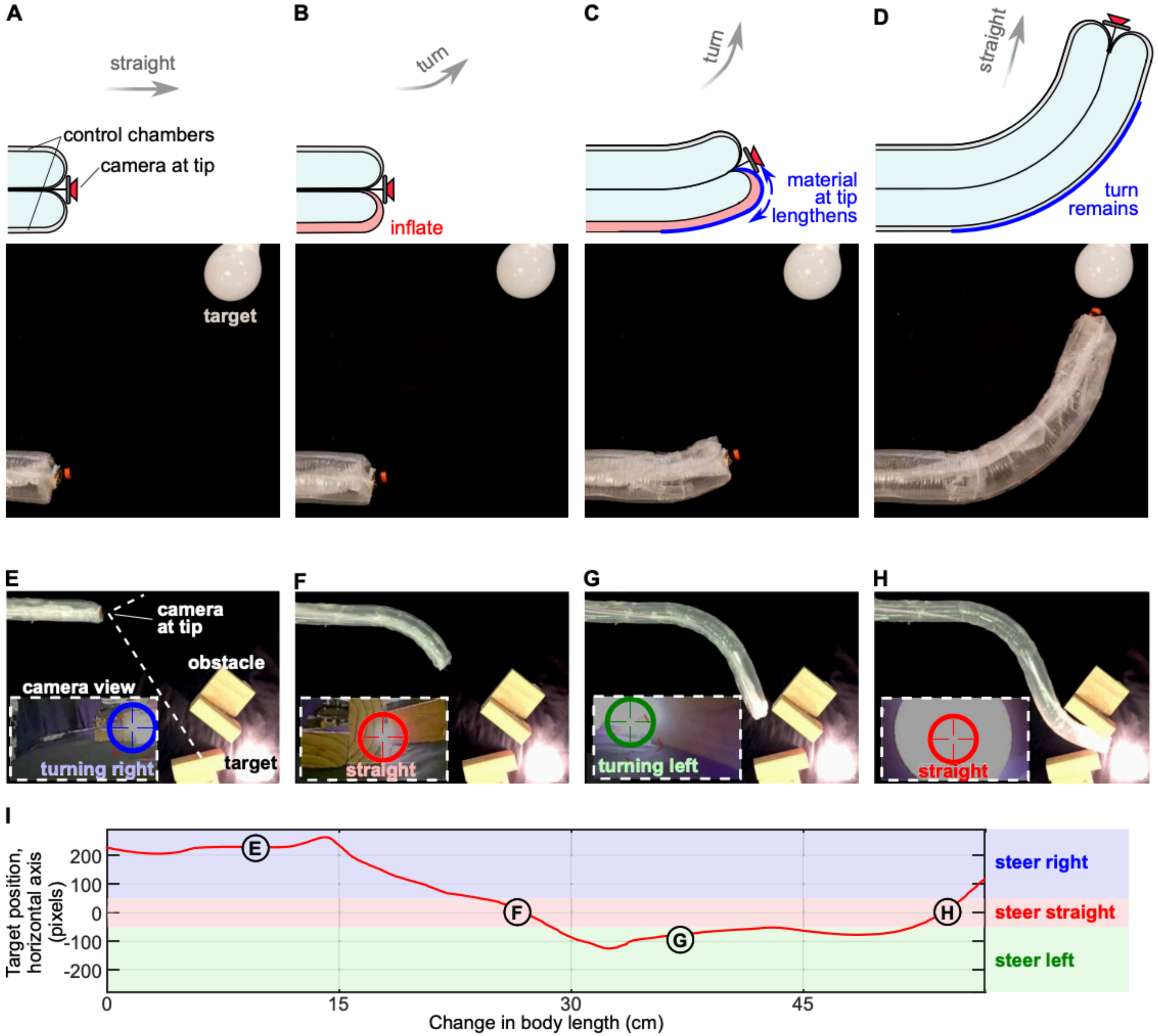


Fig. 3. Principle of asymmetric lengthening of tip enables active steering. (**A**) Implementation in a soft robot uses small pneumatic control chambers and a camera mounted on the tip for visual feedback of the environment. The camera is held in place by a cable running through the body of the robot. (**B**) To queue an upward turn, the lower control chamber is inflated. (**C**) As the body grows in length, material on the inflated side lengthens as it everts, resulting in an upward turn (see Materials and Methods and Fig.5 for details). (**D**) Once the chamber is deflated, the body again lengthens along a straight path, and the curved section remains. (**E**) A soft robot can navigate toward light using a tip-mounted camera. Inset: The view from the camera shows the target to the right. Electronically controlled solenoid valves inflate the control chamber on the left side of the robot body, resulting in the tip reorienting to the right and forming a right turn. (**F**) The target is straight ahead, and the robot steers straight. (**G**) The target is to the left, and the robot steers left. (**H**) The robot reaches the target. (**I**) Position of the target along the horizontal axis of the camera as the robot lengthens toward the target.

Control

- Small control chambers that run along the side of the robot body act as the control input; when one of these chambers is inflated , the section of the robot body that is everting from the tip on that side will be lengthen. For example, when the left channel is inflated, the left side of the tip lengthens, resulting in a right turn. See Fig.5 in next slide. Thus ,by controlling the relative pressure of these control chambers, steering is achieved .
- This method of turning is efficient and simple!
- It requires neither addition of energy (beyond the control signal) nor bulky actuators to bend an existing segment .Rather ,the turn is created at the same time as the segment using energy stored in the pressurized fluid of the main chamber.

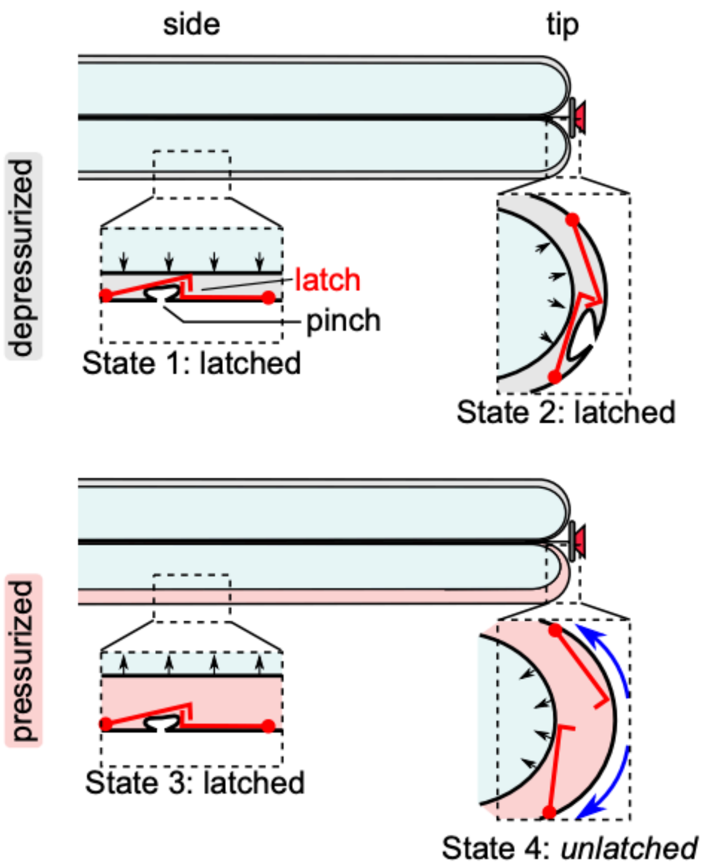


Fig. 5. Details of an implementation of a mechanism within the control chambers for selective lengthening of the sides of the soft robot. A series of latches are manufactured into the control chambers shown in Fig.3 (A to D). Each latch crosses pinched material, such that when released, the side lengthens. There are four total states. State 1: When the control chamber is depressurized and the latch is on the side, the latch remains closed. State 2: When the control chamber is depressurized and the latch is at the tip, the latch remains closed. (When a control chamber is depressurized, the pressure from the main chamber keeps the latch closed regardless of whether the latch is on the side or at the tip.) State 3: When the control chamber is pressurized and the latch is on the side, the latch remains closed. State 4: When the control chamber is pressurized and the latch is at the tip, the latch opens. (When the control chamber is pressurized, the latch remains closed if it is along a side, due to the shape of the interlocking of the latch, but the latch opens if it is at the tip because the high curvature overcomes the interlocking.)

Growth

- The presented class of soft robots shows some of the capabilities of natural cells and organisms that navigate by growth: movement through tightly constrained environments and the creation of 3D structures with the lengthening body. They tested their system ,see Figure 4A and demonstrated the insensitivity to surface characteristics See Fig.4B. It takes no more pressure to grow between two adhesive surfaces than between two polytetrafluoroethylene (PTFE) surfaces. They also demonstrated 3D structures created by lengthening a preformed body :active hook, a fire hose, and a radio antenna ,Fig, 4C .

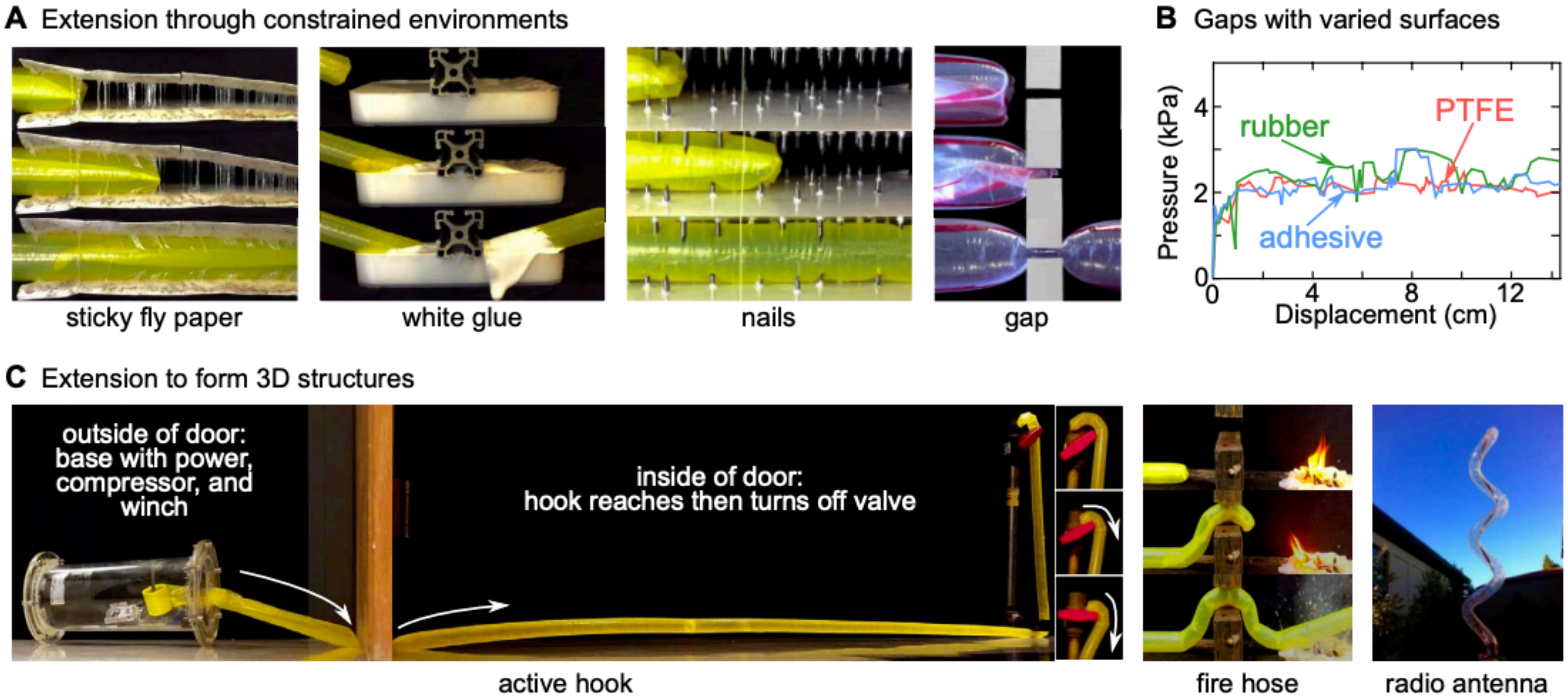


Fig. 4. Growth enables a soft robot to move its tip through constrained environments and to form 3D structures defined by the path of its tip. (**A**) A soft robot lengthens through various challenging constrained environments without active control. Instead, the robot passively deforms to navigate the obstacles. Yellow bodies, 2.5-cm diameter; clear bodies, 8-cm diameter. (**B**) The pressure required to lengthen through the gap remains relatively constant, despite vastly different surface properties of the material surrounding the gap and different displacements within the gap. Setup is shown in fig. S1. (**C**) The soft robot demonstrates the ability to lengthen into useful 3D structures.

Active Steering control with on board sensing

- The objective of the task was to steer the tip of the osft robot in two dimensions to a goal location indicated by an illuminated light bulb see Figure 6 at the next slide.
- There were three components:
- hardware overview, describes the location of the illuminated light bulb at the tip of the soft robot. Air was supplied to the main chamber of the soft robot. Electronic solenoids were used to selectively inflate the side chambers based on the commands of the vision based steering controller.
- Vision processing
- Steering Controller see Fig 6.

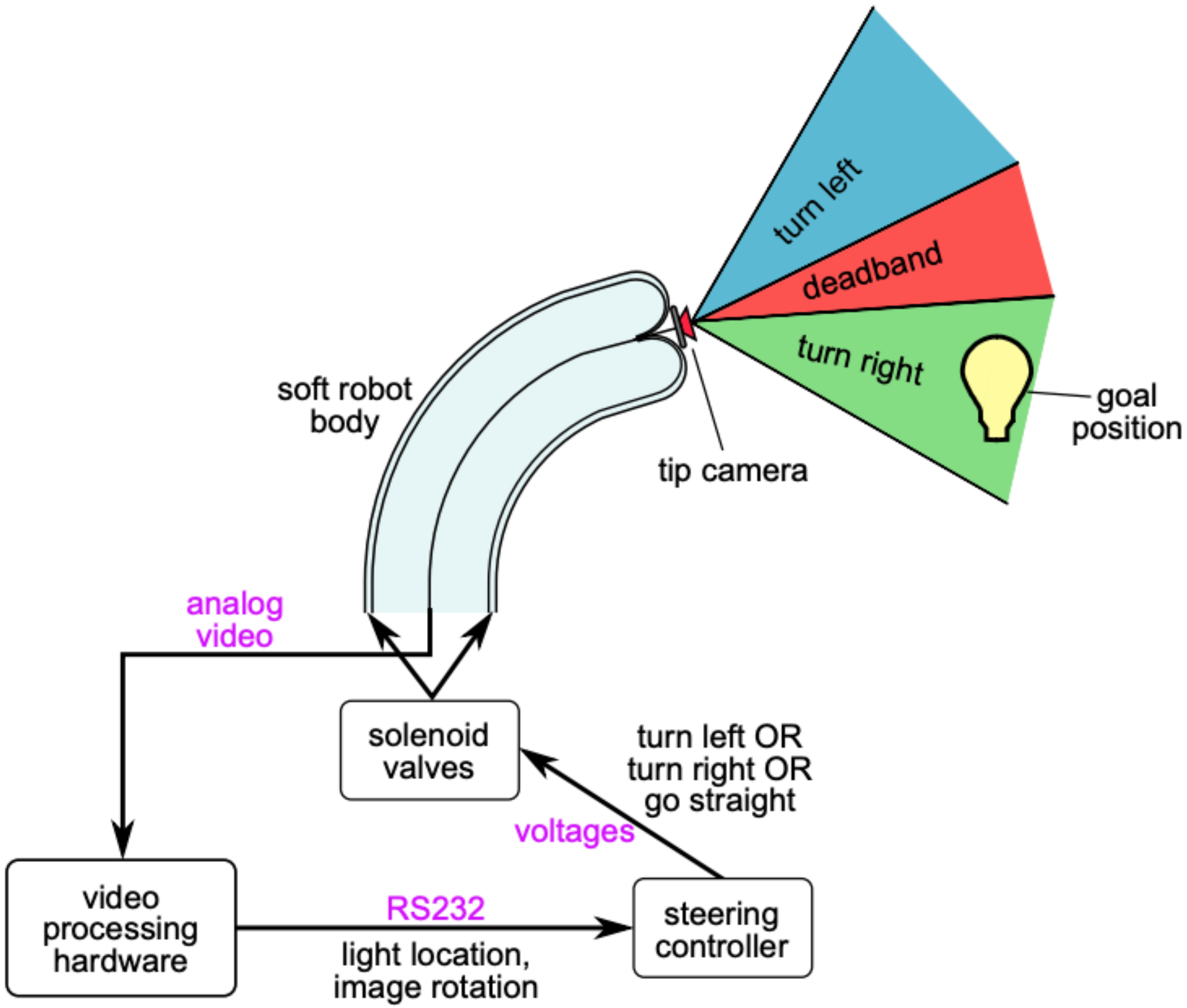


Fig. 6. Overview of active steering control system. Hardware components and a physical depiction of the steering task are shown. Electrical signal formats are labeled in purple, and their semantic meanings are labeled in black.

Conclusion

- Growth is an intriguing method for navigating the environment and is found across kingdoms and scales in nature. Although limited in range, it allows access to constrained environments and enables the creation of 3D structures along the path of movement.
- This was demonstrated by the paper form Stanford led by prof.Okamura.
- The other slides demonstrate the flexibility of soft robotics in more general. However it is also more demanding in understanding of materials (continuous mechanics) , understanding different ways of energizing these system, different ways of sensing and subsequently controlling including different ways of actuating these system.
- Questions of precision vs robustness are still open