Week 01: Introduction

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Lecture Overview

- Overall objectives
- Syllabus and grading
- Content and schedule

- How to read research articles?
- From macro to small scale robotics

Instructor: Selman Sakar

- Associate Professor at EPFL
  - Research: Microrobotics, mechanobiology, medical technology
  - Website: https://www.epfl.ch/labs/microbs/
  - Contact me for semester/master thesis projects

Course Information

- Time
  - 9:15-noon on Mondays
- Office and Email
  - MED3 2916 and selman.sakar@epfl.ch
  - Email me to arrange office hours
- Course Webpage
  - https://moodle.epfl.ch/course/view.php?id=15857
  - Check for content regularly
  - Research articles will be updated soon

Course Material

- There is no textbook
- Lecture Notes
- Review Articles
- Research Articles

Background

- ME426: Micro/Nanomechanical Devices
- Focus will be on advanced manufacturing techniques and actuation methods

Overall Objectives

- Design, manufacturing, and powering paradigms for small scale robots
- (Potential) applications of small-scale robots

- Introduce concepts like
  - Scaling laws
  - Multiphysics and multi-material microfabrication
  - Comparative analysis of available actuation/powering strategies
  - Locomotion modes (terrestrial, aquatic, flight)

- Soft skills
  - Critical reading of research articles
  - Literature review
  - Presentation and technical writing

Grading

- Weekly assignments and class participation 30%
- Paper Presentation 30%
- Final Exam 40%

Weekly Assignments

- Form groups of 5 people
- Sign up for article on Moodle
- Everyone else will send 2 questions on the articles **by Friday midnight** every week
- I will upload selected questions on Moodle and forward them to the presenting group
- Each group will present their article and answer selected questions during an exercise session (15 min)

Final Exam

- Take home exam
- Your questions will serve as the pool

Contents

- Power
- Actuation
- Manufacturing
- Locomotion
  - Swimming, flight, crawling, stick-slip motion, jumping, legged locomotion, multimode locomotion, adaptive locomotion
- Perception (without electronics)
- Manipulation
  - Precision positioners, handling (liquid and solid), cargo transport, material characterization, surgical robots,

Applications

- Microassembly and mechanical characterization
  - Speed, accuracy, and gentleness in handling small parts
  - Footprint, cost
  - Analogy: Bulldozer to move sugar cubes within a hair's width
- Surveillance and environmental monitoring
- Targeted drug delivery and microsurgery

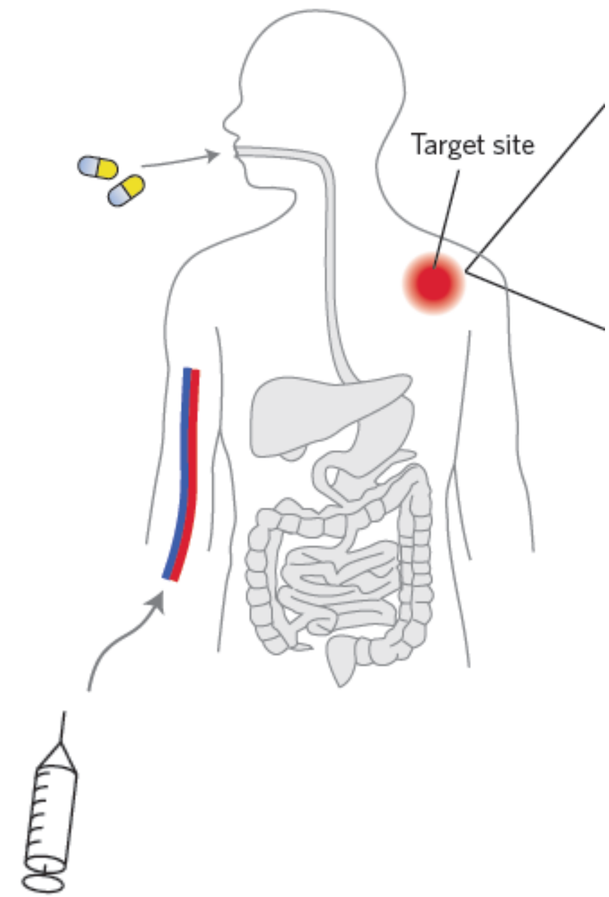
- Review articles on Moodle

Targeted Therapy

- Localized delivery of chemical and biological substances
- Localized application of energy

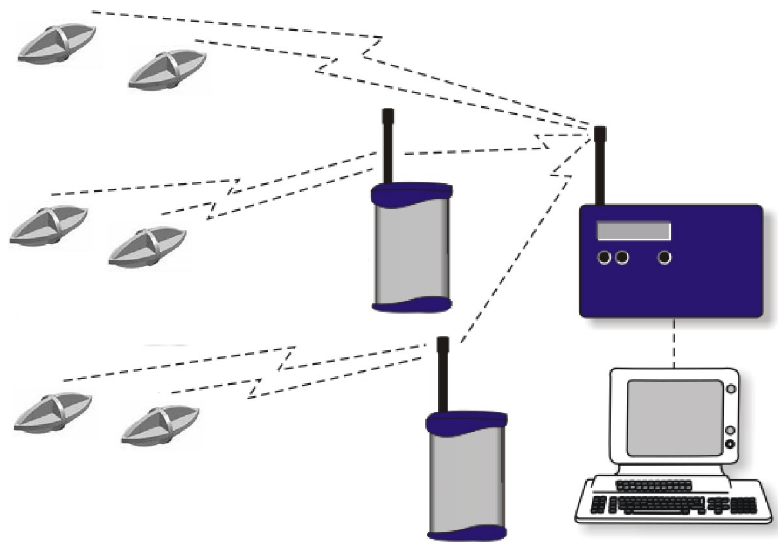
- Drug delivery
  - Currently, the whole body is subjected to the drug through the blood stream
    - Increased chances of side effects
  - A microrobot carrying a small amount of drug
    - Decreases side effects,
    - Subjects the tissue to high drug concentration

  - Local heating



Telemetry

- Micromachines can be used for transmitting information from a specific location which is difficult to obtain
  - pH and temperature of digestive track
  - Oxygen concentration in the eye
  - Urea and glucose concentration in blood
  - Detection of internal bleeding



- This information can be sent back in various ways, using
  - Radio waves
  - Visible light
  - Acoustic waves
  - Chemical signals
  - Imaging-based diagnosis

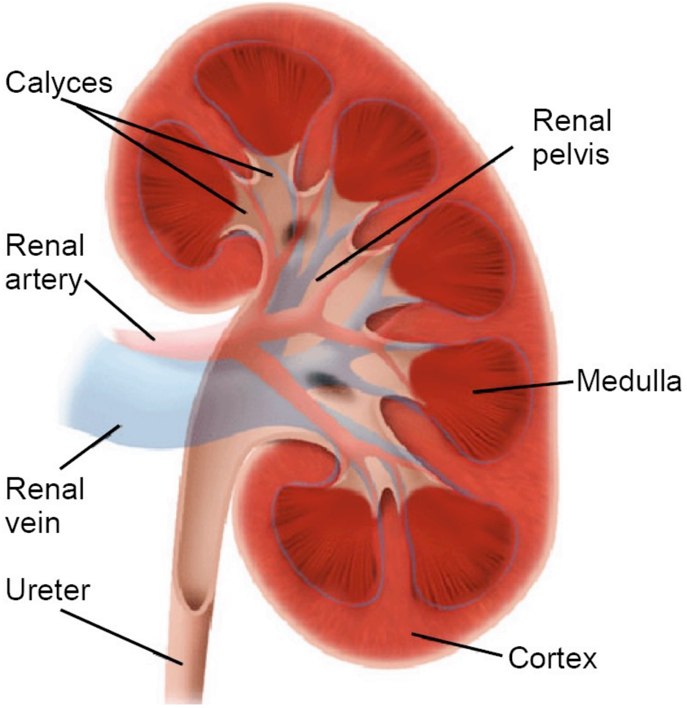
Material Removal

- Micromachines can be used to remove material by mechanical means

- Lithotomy and Lithotripsy
  - Kidney stone removal (lithotomy)
  - Kidney stone destruction (lithotripsy)

- Excision
  - Removal of tumor or blood clot

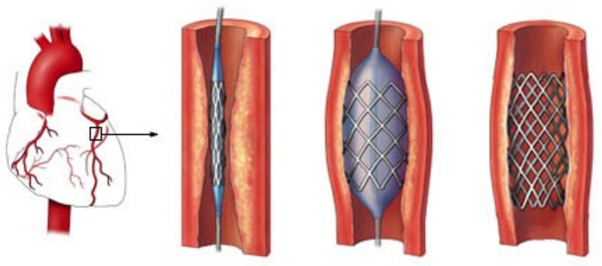
- Biopsy sampling



Deployable Structures

- Microrobot transporting and delivering deployable structures

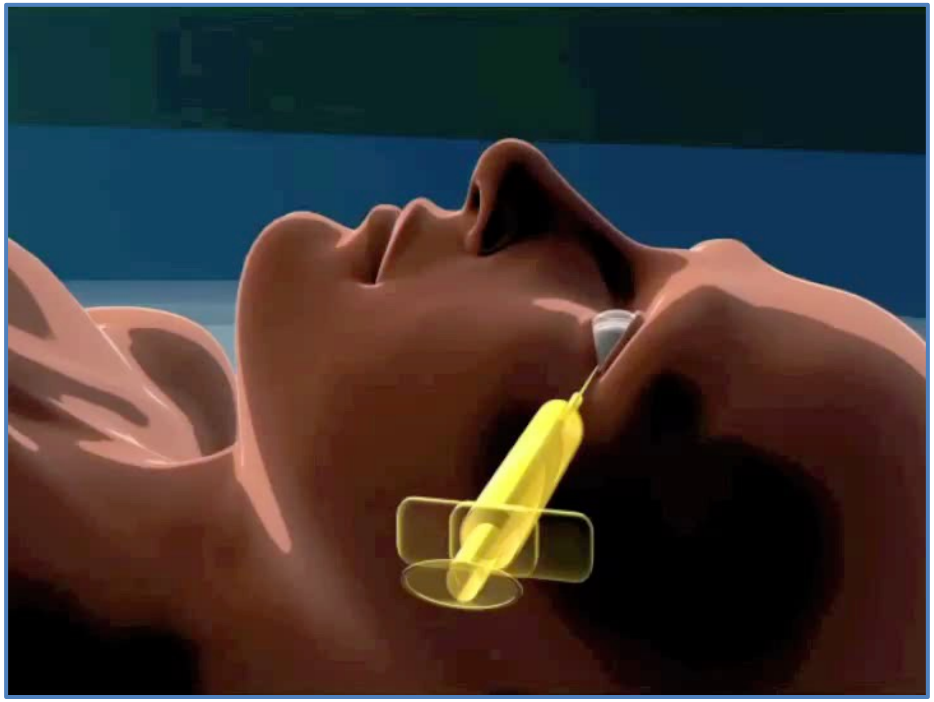
- Scaffolding
  - The structure can act a support frame, for example in
    - Nerve regeneration
    - Development of artificial organs
    - Blood vessel regrowth
  - Microrobots can be used instead of catheter-based stents
    - They would be the stent
    - They would navigate in the correct location
    - And then they would deploy

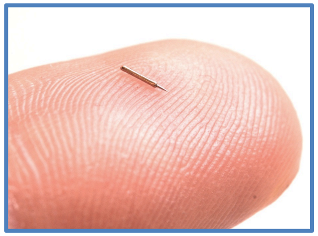


Specifications

- To access remote locations, the size of the robot should be in the millimeter or micrometer range.
- Power and control signals (tiny tethers, antenna, wireless control)
- Flow can be a significant issue
- Most of the body parts are not visible (special methods for localization) and have complex shapes (navigation)
- Lumens and cavities are filled with viscoelastic fluids

Intraocular Microrobots

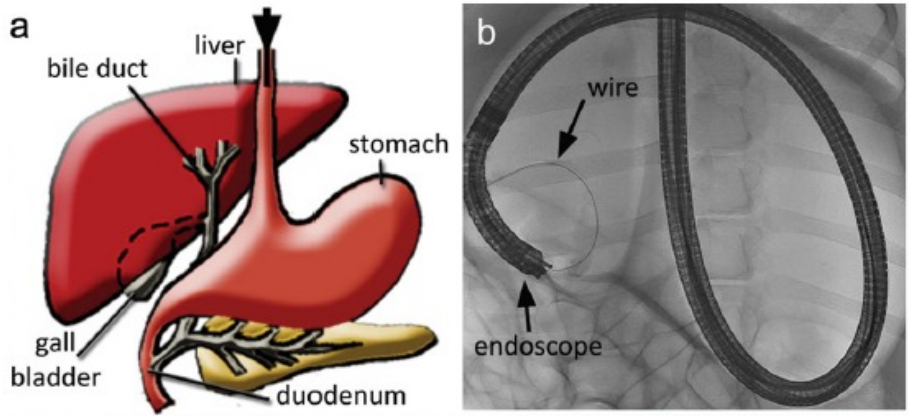


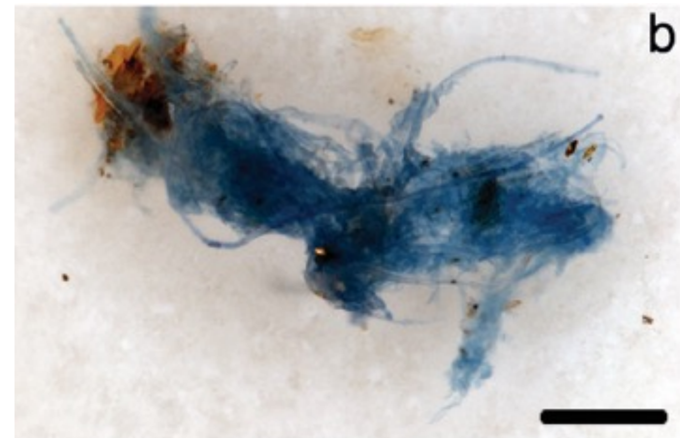


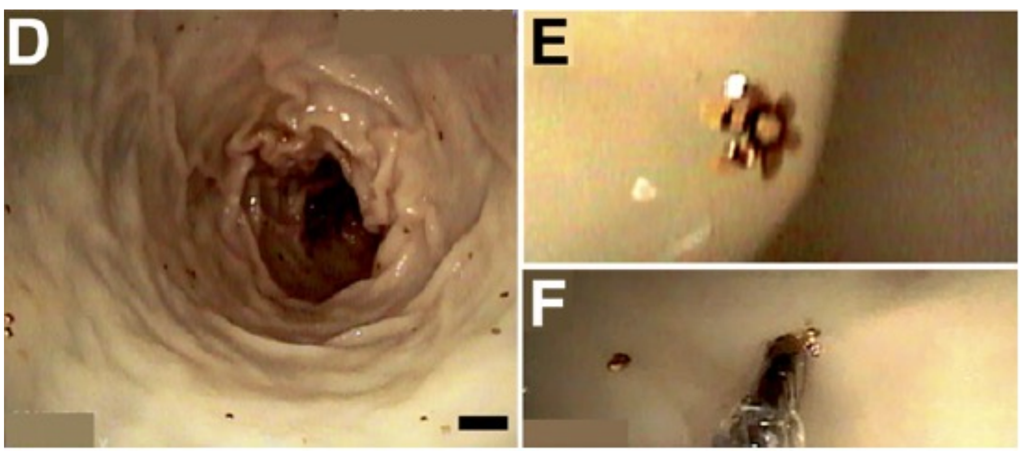
- OD: 300µm
- ID: 125µm
- Len: 2.5mm
- Coated with Au and Polypyrrole
- Fits in a 23G needle

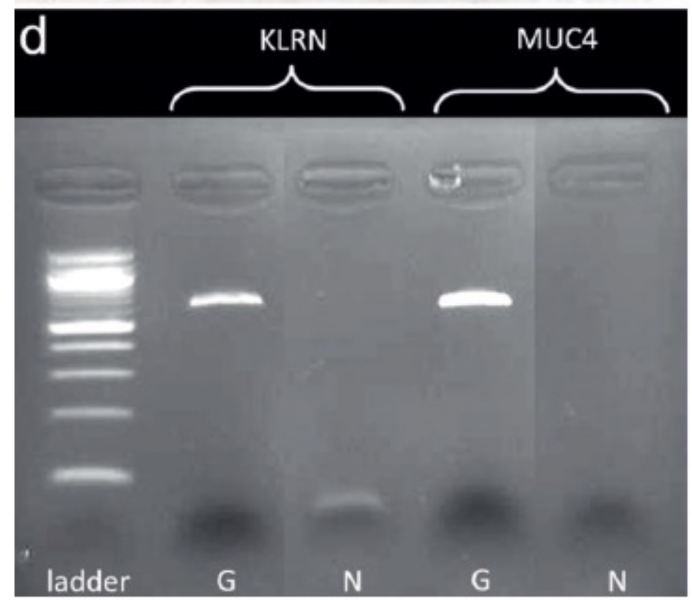
  No need for sutures

Biopsy of the Bile Duct using Microgrippers







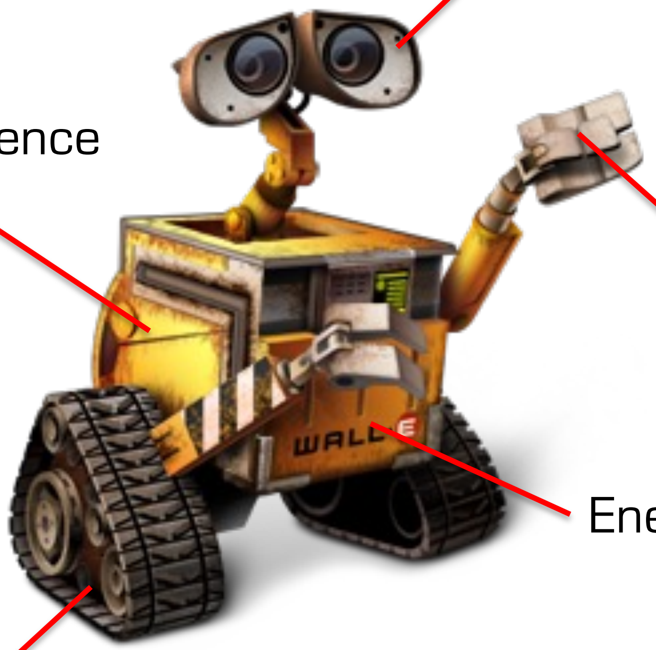


Gultepe etal, Adv Mater, 2012

Conventional Robotics

Computer Vision and Sensors

Computation and Intelligence



Manipulators

Energy Source

Locomotion

Conventional Actuators

- Electric motors (DC motors, AC motors, Stepper motor, Servo motor)
- Hydraulic and pneumatic actuators for heavy duty
- Autonomous vehicles as robots
  - Heat engines (combustion, jet engine)

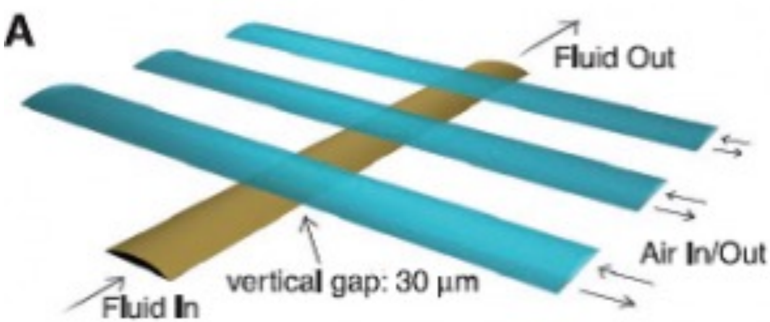
Scaling of Actuators: Electric motors

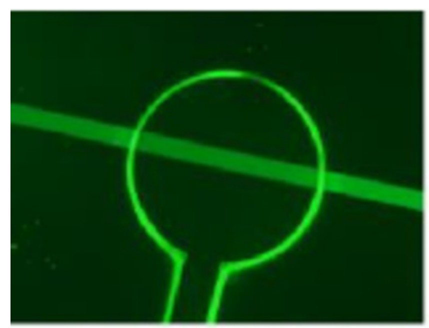
- Magnetic and inertial forces scale poorly into the micro domain
- Miniaturization of many complicated components such as coils, magnets, and bearings
- Severe torque dissipation due to the scaling
- Dominant role of electrostatics, surface tension, viscous forces, chemical reactions, heat transfer, vibrations
- State of the art motors: centimeter sized

- Review article on Moodle

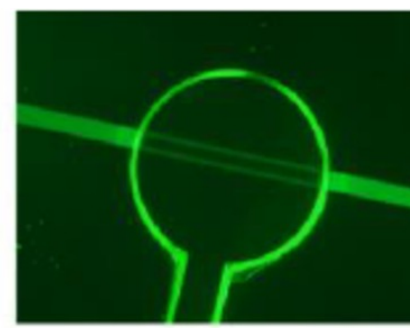
Scaling of Actuators: Pneumatic Actuators

- Pneumatics actually scale fine (microfluidics and valves) but how do we control pressure without tethers?





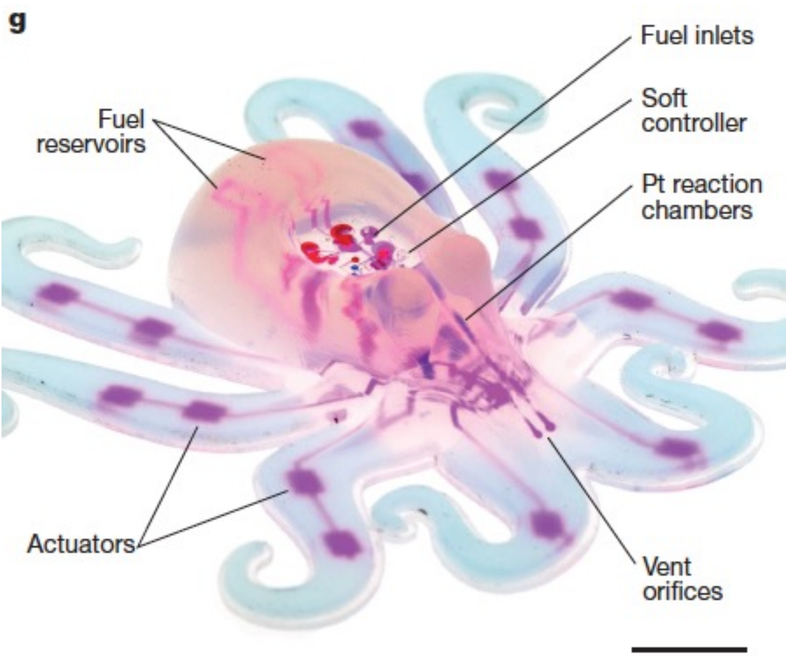
Quake Valve Off

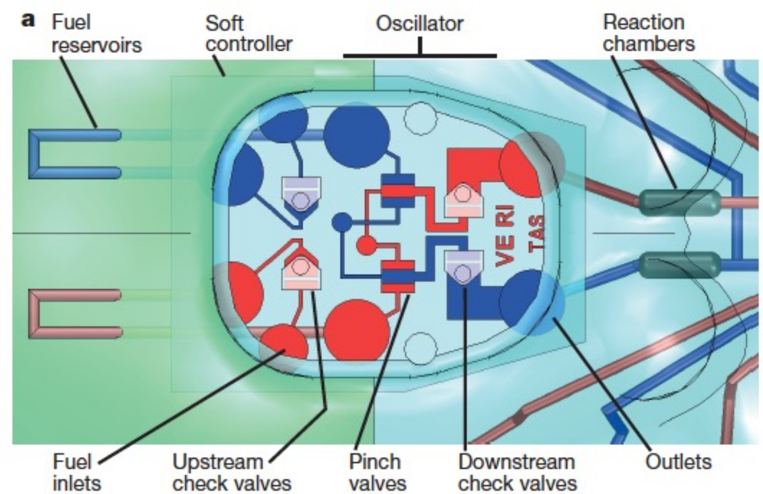


Quake Valve On

Scaling of Actuators: Pneumatic Actuators

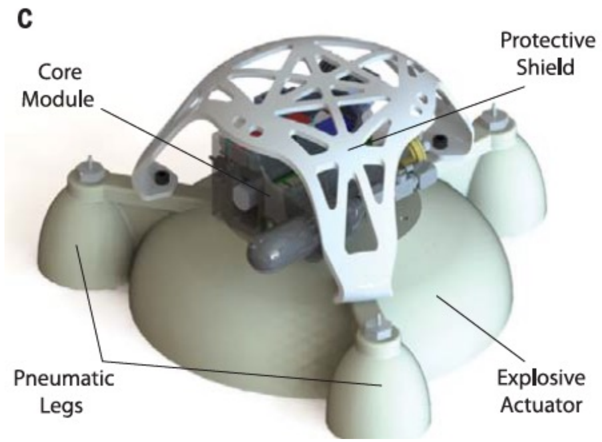
- On-board generation of gas pressure?

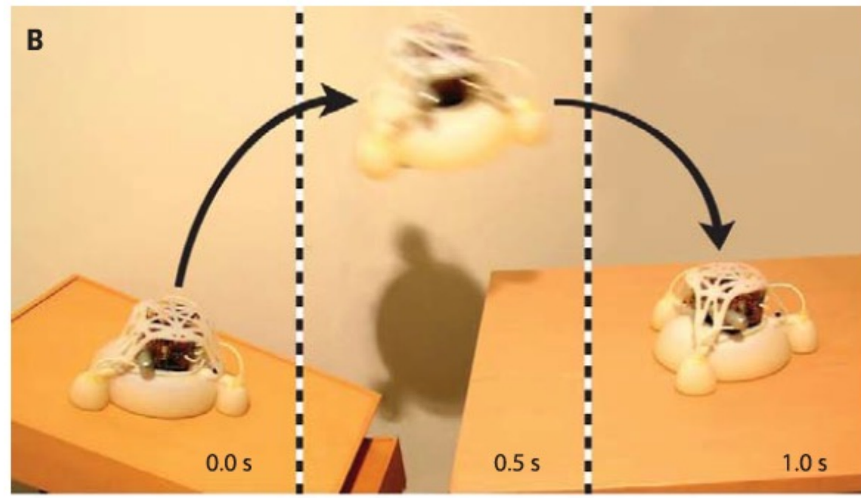


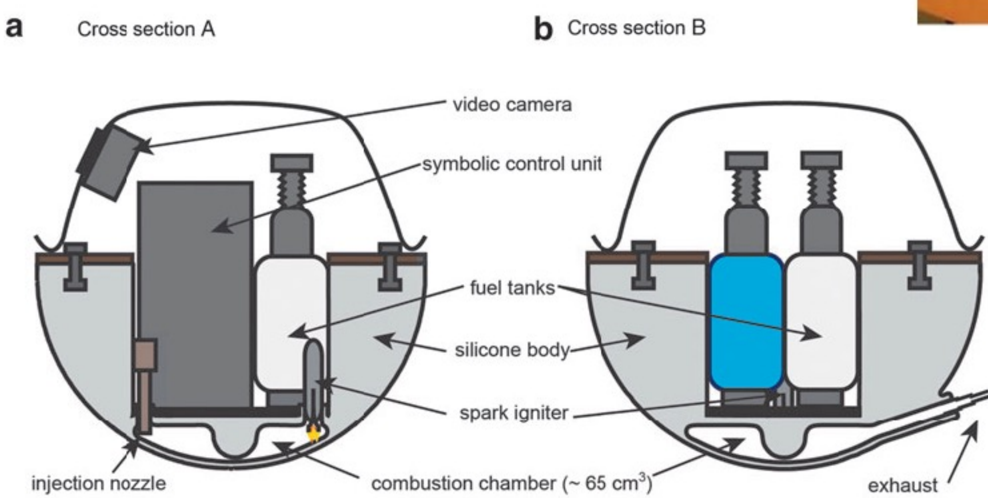


Scaling of Actuators: Heat Engines

- Combustion



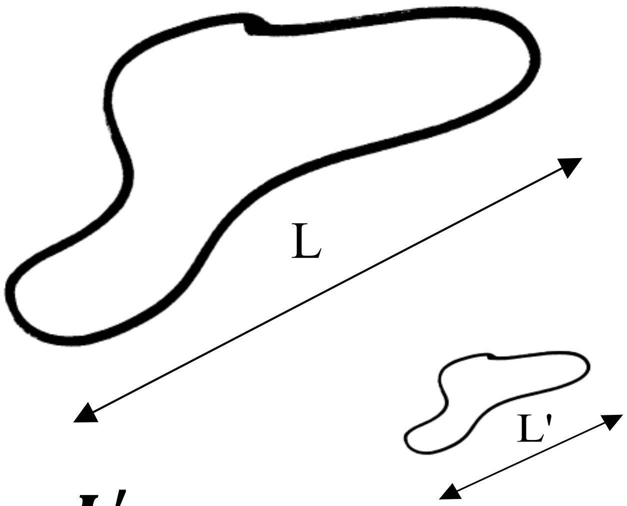




Scaling of Mechanisms: Efficiency and Manufacturing

- Pin joints → compliant mechanisms (surface effects)
- CNC → cleanroom (precision)
- Printers → direct laser writing (two-photon polymerization)
- 3D complexity: folding, self-assembly, capillary forces

Scaling Laws



$$\lambda = \frac{L'}{L}$$

Magnitude	Scaling factor
length (L)	λ
area (A)	λ^2
volume (V), mass (m)	λ^3
surface to volume ratio	λ^{-1}
stiffness (k)	λ
resonance frequency (f_0)	λ^{-1}
mass responsivity ($\Re$)	λ^{-4}
thermal time constant (τ)	λ

Scaling Laws

- Depending on the size-scale different physical effects become more or less important

- At small scale, inertial forces become less important as mass scales $\sim L^3$ (keeping density constant)

    - Resonant frequencies go very high

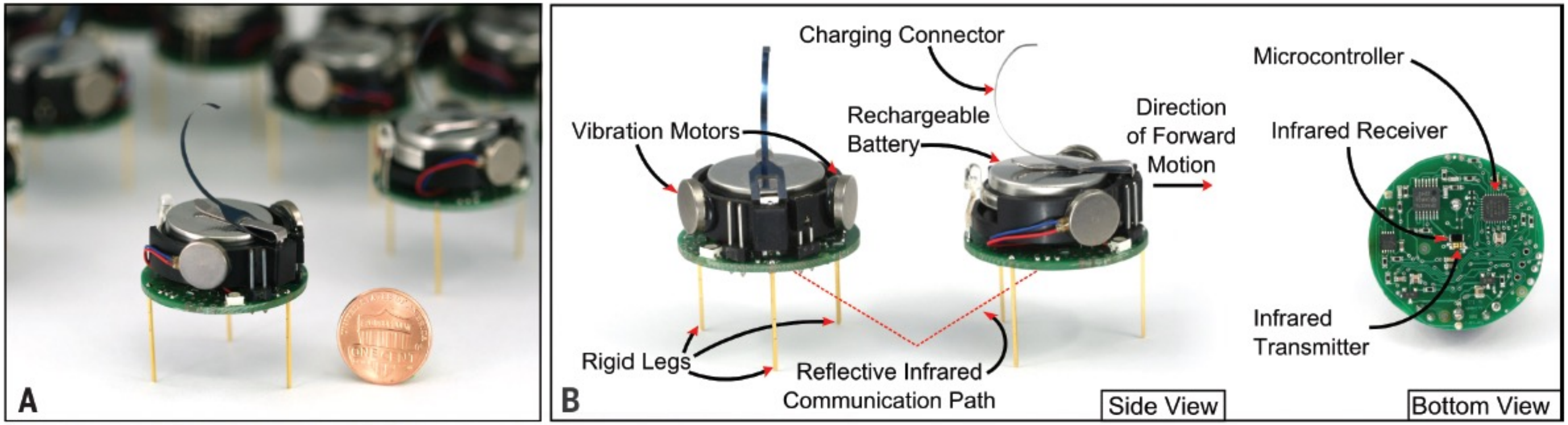
    - Thermal equilibrium is achieved faster

    - Electromagnetic forces dominate mechanics

    - Laminar flow dominates fluidics

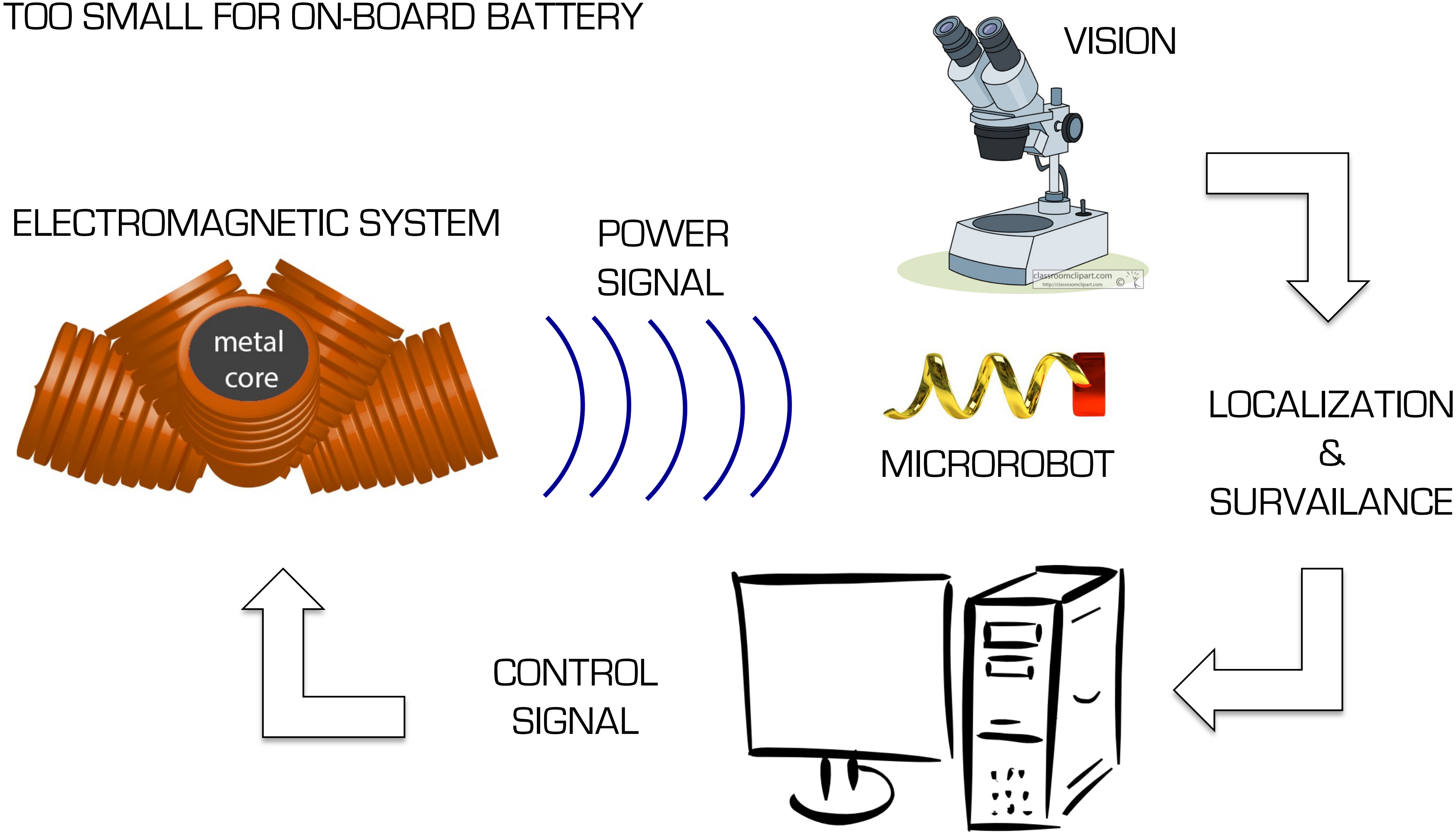
At the interface

- Vibration motors and battery
- Smallest battery: few millimeters



Wirelessly Powered and Controlled Microrobots

TOO SMALL FOR ON-BOARD BATTERY



Power

- Electric power: cables, electrostatic charge, electric fields, batteries
- Magnetic fields: Uniform (rotation, oscillation, vibration), Field Gradients, RF
- Pressure waves: Substrate vibration, Surface acoustic waves, bulk acoustic waves, acoustofluidics
- Light: Photothermal effects, phase transitions, photovoltaics
- On-board power generation: Catalytic reactions, energy harvesting (i.e. osmosis), hydropower, biological actuators

- Power requirements for intended tasks? Power density?

Actuation

- Solid-state actuators: Piezoelectric, magnetostrictive, shape memory
- Liquid crystal elastomers
- Electrostatic actuators and electroactive polymers
- Acoustic streaming
- Catalytic motors
- Thermal actuators
- Artificial swimmers (helices, elastica)
- Biological actuators
- Protein and DNA-based nanoactuators

Manufacturing and Materials

- Popup MEMS (folding, buckling)
- Direct laser writing and stereolithography
- Laser micromachining
- Soft lithography and microfluidics
- Chemical synthesis
- Electrodeposition
- Polymers, metals, semiconductors, elastomers, hydrogels, nucleic acids, nanocomposites

Tentative Schedule

- Solid-state actuators and Popup MEMS
- Electrostatic actuators and electroactive polymers
- Vibrations, resonant actuators, and micromanipulation
- Low Reynolds Number swimmers
- Programmable magnetic soft matter
- Light-matter interactions and optomechanical actuators
- Acoustofluidics
- Catalytic motors and jet propulsion
- DNA machines
- Biological actuators and machines

Article 1

Insect-scale jumping robots enabled by a dynamic buckling cascade

Millions of years of evolution have allowed animals to develop unusual locomotion capabilities. A striking example is the legless-jumping of click beetles and trap-jaw ants, which jump more than 10 times their body length. Their delicate musculoskeletal system amplifies their muscles' power. It is challenging to engineer insect-scale jumpers that use onboard actuators for both elastic energy storage and power amplification. Typical jumpers require a combination of at least two actuator mechanisms for elastic energy storage and jump triggering, leading to complex designs having many parts. Here, we report the new concept of dynamic buckling cascading, in which a single unidirectional actuation stroke drives an elastic beam through a sequence of energy-storing buckling modes automatically followed by spontaneous impulsive snapping at a critical triggering threshold. Integrating this cascade in a robot enables jumping with unidirectional muscles and power amplification (JUMPA). These JUMPA systems use a single lightweight mechanism for energy storage and release with a mass of 1.6 g and 2 cm length and jump up to 0.9 m, 40 times their body length. They jump repeatedly by reengaging the latch and using coiled artificial muscles to restore elastic energy. The robots reach their performance limits guided by theoretical analysis of snap-through and momentum exchange during ground collision. These jumpers reach the energy densities typical of the best macroscale jumping robots, while also matching the rapid escape times of jumping insects, thus demonstrating the path toward future applications including proximity sensing, inspection, and search and rescue.

Article 2

Acrobatics at the insect scale: A durable, precise, and agile micro–aerial robot

Aerial insects are exceptionally agile and precise owing to their small size and fast neuromotor control. They perform impressive acrobatic maneuvers when evading predators, recovering from wind gust, or landing on moving objects. Flapping-wing propulsion is advantageous for flight agility because it can generate large changes in instantaneous forces and torques. During flapping-wing flight, wings, hinges, and tendons of pterygote insects endure large deformation and high stress hundreds of times each second, highlighting the outstanding flexibility and fatigue resistance of biological structures and materials. In comparison, engineered materials and microscale structures in subgram micro–aerial vehicles (MAVs) exhibit substantially shorter lifespans. Consequently, most subgram MAVs are limited to hovering for less than 10 seconds or following simple trajectories at slow speeds. Here, we developed a 750-milligram flapping-wing MAV that demonstrated substantially improved lifespan, speed, accuracy, and agility. With transmission and hinge designs that reduced off-axis torsional stress and deformation, the robot achieved a 1000-second hovering flight, two orders of magnitude longer than existing subgram MAVs. This robot also performed complex flight trajectories with under 1-centimeter root mean square error and more than 30 centimeters per second average speed. With a lift-to-weight ratio of 2.2 and a maximum ascending speed of 100 centimeters per second, this robot demonstrated double body flips at a rotational rate exceeding that of the fastest aerial insects and larger MAVs. These results highlight insect-like flight endurance, precision, and agility in an at-scale MAV, opening opportunities for future research on sensing and power autonomy.

Article 3

Sunlight-powered sustained flight of an ultralight micro aerial vehicle

Limited flight duration is a considerable obstacle to the widespread application of micro aerial vehicles (MAVs)[1–3], especially for ultralightweight MAVs weighing less than 10 g, which, in general, have a flight endurance of no more than 10 min (refs. 1,4). Sunlight power[5–7] is a potential alternative to improve the endurance of ultralight MAVs, but owing to the restricted payload capacity of the vehicle and low lift-to-power efficiency of traditional propulsion systems, previous studies have not achieved untethered sustained flight of MAVs fully powered by natural sunlight[8,9]. Here, to address these challenges, we introduce the CoulombFly, an electrostatic flyer consisting of an electrostatic-driven propulsion system with a high lift-to-power efficiency of 30.7 g W^{-1} and an ultralight kilovolt power system with a low power consumption of 0.568 W, to realize solar-powered sustained flight of an MAV under natural sunlight conditions (920 W m^{-2}). The vehicle's total mass is only 4.21 g, within 1/600 of the existing lightest sunlight-powered aerial vehicle[6].

Article 4

Electronically configurable microscopic metasheet robots

Shape morphing is vital to locomotion in microscopic organisms but has been challenging to achieve in sub-millimetre robots. By overcoming obstacles associated with miniaturization, we demonstrate microscopic electronically configurable morphing metasheet robots. These metabots expand locally using a kirigami structure spanning five decades in length, from 10 nm electrochemically actuated hinges to 100 μm splaying panels making up the ~1 mm robot. The panels are organized into unit cells that can expand and contract by 40% within 100 ms. These units are tiled to create metasheets with over 200 hinges and independent electronically actuating regions that enable the robot to switch between multiple target geometries with distinct curvature distributions. By electronically actuating independent regions with prescribed phase delays, we generate locomotory gaits. These results advance a metamaterial paradigm for microscopic, continuum, compliant, programmable robots and pave the way to a broad spectrum of applications, including reconfigurable micromachines, tunable optical metasurfaces and miniaturized biomedical devices.

Article 5

Magnetically programmed diffractive robotics

Conrad L. Smart[1]†, Tanner G. Pearson[2]†, Zexi Liang[1,3], Melody X. Lim[1,3], Mohamed I. Abdelrahman[4], Francesco Monticone[4], Itai Cohen[1,3], Paul L. McEuen[1,3]*

Microscopic robots with features comparable with the wavelength of light offer new ways of probing the microscopic world and controlling light at the microscale. We introduce a new class of magnetically controlled microscopic robots (microbots) that operate at the visible-light diffraction limit, which we term diffractive robots. We combined nanometer-thick mechanical membranes, programmable nanomagnets, and diffractive optical elements to create untethered microbots small enough to diffract visible light and flexible enough to undergo complex reconfigurations in millitesla-scale magnetic fields. We demonstrated their applications, including subdiffractive imaging by using a variant of structured illumination microscopy, tunable diffractive optical elements for beam steering and focusing, and force sensing with piconewton sensitivity.

Article 6

A Human-Scale Clinically Ready Electromagnetic Navigation System for Magnetically Responsive Biomaterials and Medical Devices

Magnetic navigation systems are used to precisely manipulate magnetically responsive materials enabling the realization of new minimally invasive procedures using magnetic medical devices. Their widespread applicability has been constrained by high infrastructure demands and costs. The study reports on a portable electromagnetic navigation system, the Navion, which is capable of generating a large magnetic field over a large workspace. The system is easy to install in hospital operating rooms and transportable through health care facilities, aiding in the widespread adoption of magnetically responsive medical devices. First, the design and implementation approach for the system are introduced and its performance is characterized. Next, in vitro navigation of different microrobot structures is demonstrated using magnetic field gradients and rotating magnetic fields. Spherical permanent magnets, electroplated cylindrical microrobots, microparticle swarms, and magnetic composite bacteria-inspired helical structures are investigated. The navigation of magnetic catheters is also demonstrated in two challenging endovascular tasks: 1) an angiography procedure and 2) deep navigation within the circle of Willis. Catheter navigation is demonstrated in a porcine model in vivo to perform an angiography under magnetic guidance.

Article 7

Wireless flow-powered miniature robot capable of traversing tubular structures

Wireless millimeter-scale robots capable of navigating through fluid-flowing tubular structures hold substantial potential for inspection, maintenance, or repair use in nuclear, industrial, and medical applications. However, prevalent reliance on external powering constrains these robots' operational range and applicable environments. Alternatives with onboard powering must trade off size, functionality, and operation duration. Here, we propose a wireless millimeter-scale wheeled robot capable of using environmental flows to power and actuate its long-distance locomotion through complex pipelines. The flow-powering module can convert flow energy into mechanical energy, achieving an impeller speed of up to 9595 revolutions per minute, accompanied by an output power density of 11.7 watts per cubic meter and an efficiency of 33.7%. A miniature gearbox module can further transmit the converted mechanical energy into the robot's locomotion system, allowing the robot to move against water flow at an average rate of up to 1.05 meters per second. The robot's motion status (moving against/with flow or pausing) can be switched using an external magnetic field or an onboard mechanical regulator, contingent on different proposed control designs. In addition, we designed kirigami-based soft wheels for adaptive locomotion. The robot can move against flows of various substances within pipes featuring complex geometries and diverse materials. Solely powered by flow, the robot can transport cylindrical payloads with a diameter of up to 55% of the pipe's diameter and carry devices such as an endoscopic camera for pipeline inspection, a wireless temperature sensor for environmental temperature monitoring, and a leak-stopper shell for infrastructure maintenance.

Article 8

Multiorifice acoustic microrobot for boundary-free multimodal 3D swimming

The emerging new generation of small-scaled acoustic microrobots is poised to expedite the adoption of microrobotics in biomedical research. Recent designs of these microrobots have enabled intricate bioinspired motions, paving the way for their real-world applications. We present a multiorifice design of air-filled spherical microrobots that convert acoustic wave energy to efficient propulsion through a resonant encapsulated microbubble. These microrobots can swim boundary-free in three-dimensional (3D) space while switching between various frequency-dependent locomotion modes. We explore the locomotion dynamics of microrobots with diameters ranging from 10 μm to 100 μm, focusing on their boundary-free 3D swimming and multimodal locomotion in response to acoustic stimuli below 1 MHz. Further, we elucidate the dynamics of these microrobots, featuring a single multiorifice cavity, which contributes to complex acoustic streaming and facilitates swift, unrestricted movements. Finally, we demonstrate that incorporating microrobots with additional nickel and gold layers significantly enhances their steering and visibility in optoacoustic and ultrasound imaging, enabling the development of the next generation of microrobots in healthcare applications.

Article 9

3D printed large amplitude torsional microactuators powered by ultrasound

Here, we introduce a design, fabrication, and control methodology for large amplitude torsional microactuators powered by ultrasound. The microactuators are 3D printed from two polymers with drastically different elastic moduli as a monolithic compliant mechanism, and contain precisely engineered capsules with multiple orifices that serve as stators and rotors. Secondary acoustic radiation forces generated among the encapsulated air bubbles controllably rotate the rotor that is supported and stabilized by two torsion bars. The capsules are designed according to the simulations of an analytical model that captures the dynamics of the water-air interface vibrations, which we rigorously validate using a laser Doppler vibrometer and phase-contrast imaging. An in-depth experimental sensitivity analysis is conducted to optimize the arrangement of the rotor and the stators. Integration of experimental results with finite element analysis of the twisting bars and analytical modelling of acoustic phenomena allows us to compute the secondary acoustic radiation forces and the angular displacement of the rotor for a given input pressure. The versatility of the design framework and the robust performance of the printed actuators enable the development of a new class of microscale machines and soft robotic devices that are actuated and controlled by sound waves.

Article 10

The multifunctional use of an aqueous battery for a high capacity jellyfish robot

The batteries that power untethered underwater vehicles (UUVs) serve a single purpose: to provide energy to electronics and motors; the more energy required, the bigger the robot must be to accommodate space for more energy storage. By choosing batteries composed primarily of liquid media [e.g., redox flow batteries (RFBs)], the increased weight can be better distributed for improved capacity with reduced inertial moment. Here, we formed an RFB into the shape of a jellyfish, using two redox chemistries and architectures: (i) a secondary $ZnBr_2$ battery and (ii) a hybrid primary/secondary ZnI_2 battery. A UUV was able to be powered solely by RFBs with increased volumetric (Q ~ 11 ampere-hours per liter) and areal (108 milliampere-hours per square centimeter) energy density, resulting in a long operational lifetime (T ~ 1.5 hours) for UUVs composed of primarily electrochemically energy-dense liquid (~90% of the robot's weight).

How to read and present the articles?

- Design and performance specifications: what is the intended use?
- Rationale behind design and material choices
- Fabrication protocol
- Operation principle
- Evaluation of performance (precision, speed, capabilities)

- Criticism: writing, presentation of results, potential

How to read and present the articles?

- Make sure you go through supplementary movies
- Google technical keywords (group website)
- Email me if you cannot figure out a key step

Next steps

- Form groups by Friday
- Self organization on Moodle

- Read the review articles