Micro-Swimmers and Soft-Robotics

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Abstracts Book

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Multifunctional Helical Nanoswimmers

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Abstract (250 words)

Helical nanoswimmers driven by magnetic fields can provide mechanical information about their local surrounding with sub-micron spatial resolution. We describe theory and experiments where this powerful system has been used to probe complex, heterogenous biological environments, such as the intracellular environment, as well as the extracellular matrix. The swimmers can be used for novel cargo manipulation applications, including living biomaterials Finally, we will describe techniques to maneuver and position identical nanoswimmers in an independent manner, as well as render them autonomous.

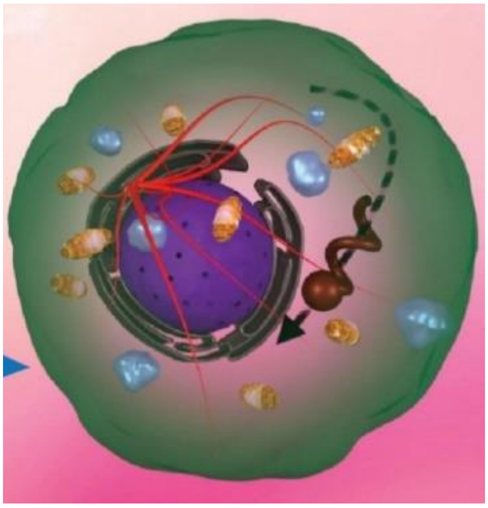

Figure 1: Helical nanoswimmers probe the inside of a living cell

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Dynamics of flexible ferromagnetic filaments

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Flexible ferromagnetic filaments may be created artificially [1] and exist in nature (magnetotactic bacteria). Their behavior in an external field has interesting features. At magnetic field inversion they make a loop which relaxes through the third dimension. In an AC field of sufficiently high frequency a filament orients perpendicularly to the field. These properties enable the creation of self-propelling magnetic microdevices. In a rotating magnetic field the filament exhibits both synchronous and asynchronous regimes [2]. These regimes are studied experimentally in [3] using chains of ferromagnetic particles linked by biotinized DNA fragments. It is known that a rigide dipole in a rotating field has coexisting fixed points (centers) and periodic trajectories. Near the centers the dipole carries out precessional motion in the frame of the rotating field. The situation is structurally unstable - for example, by applying a small field along the angular velocity of a rotating field, centers become stable focal points. The behavior of flexible ferromagnetic filaments as shown numerically is similar – in the range of the frequencies of the rotating field corresponding to the asynchronous planar regime the filament carries out the precessional regime synchronous with the field.

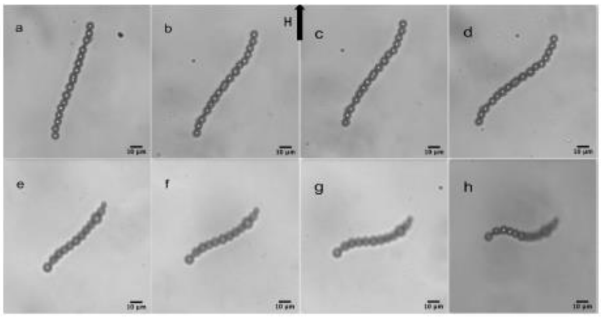

Figure 1: Two flexible magnetic filaments under a rotating field H=8.6 Oe. Filament with L=67.4 µm at (a) 0.2Hz,(b) 0.3 Hz,(c)=0.4 Hz and (d) 0.6 Hz. Filament with L=50.5 µm at € 1.0 Hz, (f) 1.5 Hz, (g)= 2.0 Hz and (h) 3.0 Hz. In (h) the filament moves out of imaging plane.

Acknowledgement. The work is financially supported by M.era-net project FMF No.1.1.1.5/ERANET/18/04.

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From Razor Clams to Robots: Drawing Engineering Inspiration from Natural Systems

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Many natural systems have evolved optimal strategies to perform certain tasks -- climbing, sensing, swimming -- within the limits set by the laws of physics. This observation can be used both to guide engineering design, and to gain insights into the form and function of biological systems. In this talk I will discuss both of these themes in the context of crawling snails, digging clams, and swimming fish. We will discover how an analysis of the physical principles exploited by snails and clams (localized fluidization for clams and adhesion via shear-thinning rheologies for snails) leads to the development of novel robotic diggers and crawlers (RoboSnail and RoboClam).

Regarding swimming organisms, we present an analysis of undulatory propulsion for slender animals and show that optimally efficient swimming kinematics can be characterized through a single dimensionless parameter. Furthermore, the optimal kinematics can be well-approximated by tuning the elasticity of the swimmer's tail. Optimal swimming kinematics are demonstrated with a simple robot.

Figure 1: Razor clam (left) and its bio-inspired counterpart, Roboclam (right).

Acknowledgement. This work was supported by NSF and ARO.

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Locomotion by shape control in nature and technology

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Abstract

In recent years, we have studied locomotion and shape control in several biological systems using a broad range of tools ranging from theoretical and computational mechanics, to experiment and observations at the microscope, to manufacturing of prototypes.

A particularly interesting case study is provided by *Euglena gracilis* [1]. This unicellular protist is particularly intriguing because it can adopt different motility strategies: swimming by flagellar propulsion, or crawling thanks to large amplitude shape changes of the whole body (a behavior known as "metaboly", or "amoeboid motion"). The shape changes required for the two strategies are completely different and consist of bending waves along the flagellum in swimming motility, peristaltic expansion/contraction waves of the body in crawling motility. Interestingly, however, both the general morphing principle and its embodiment in the microscopic architecture of the active structural elements capable of enforcing the shape changes are the same. Shape changes are achieved by Gaussian morphing [2], the paradigm by which curvature can be produced by differential in-plane stretches of the mid-surface (the tubular shell of the flagellum in one case, the body envelope in another). These stretches are in turn produced by molecular motors walking along microtubules, causing the bending of microtubule bundles and the twisting of pellicle strips.

The behavior displayed by the organism has been observed under the microscope, and reproduced quantitatively thanks to mathematical and computational models [1]. The detailed understanding of the mechanics of the shape-shifting mechanism in terms of the body architecture provides the basis to design new, bio-inspired, morphable structures [3,4].

We will survey our most recent findings in this stream of research, obtained in collaboration with M. Arroyo, A. Beran, G. Cicconofri, and G. Noselli.

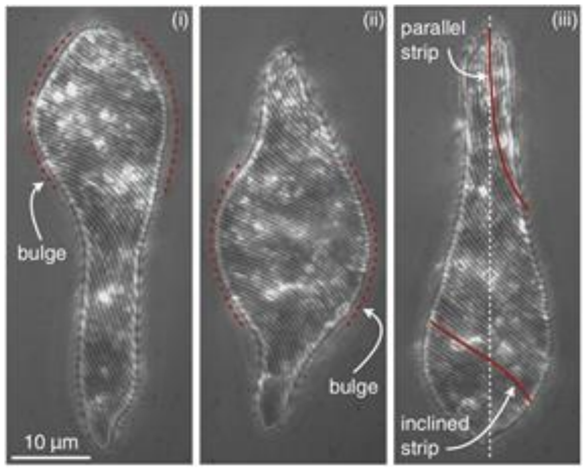

Figure 1: Shape changes in *Euglena gracilis* induced by active surface shears, adapted from [1].

Acknowledgement. This work was supported by the ERC Advanced Grant 340685-MicroMotility.

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Shape-morphing by inflation

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Soft robotics relies on the controlled active and continuous deformation of an elastic medium. Here we are interested in elastic thin sheets.

In such slender systems, geometry imposes a strong constraint on shape morphing. Indeed, if in-plane distances are conserved, so is the Gaussian curvature. Large shape changes therefore require metric changes of the surface.

Distorting the metric can be achieved by inhomogeneous swelling in hydrogels [1,2], or through sliding mechanisms in Euglena [3], or in liquid crystals elastomer [4].

Here we show two strategies for shape changing based on in-plane distance changes:

- anisotropic expansion of a network of pressurized channels in an elastomeric plate (baromorphs [5]).
- anisotropic apparent retraction of arways obtained by sealing two flat pieces of fabric [6].

Both systems respond to pressurization, and may lead to rather large and relatively stiff structures. Despite making use of a network of cavities, the mechanics involved are very different (lateral expansion vs lateral retraction).

We also study the inverse problem of designing the geometry of airways that will lead to a desired target shape through inflation.

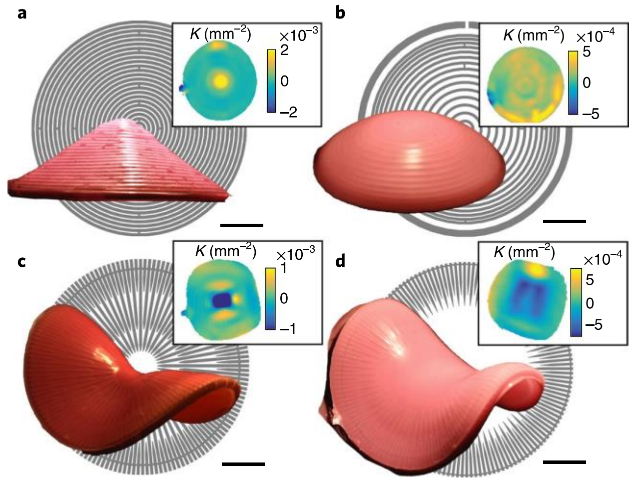

Figure 1: **Collection of 3D shapes obtained by the buckling of baromorphs under pressure.**

Acknowledgement. This work was supported by ANR Smart.

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Programmable Magnetic Micromachines

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Abstract: I will present recent work in which we have created micromachines that can be encoded and reencoded to morph into a variety of shapes. First, I will describe magnetic quadrupole modules that are able to form stable and frustration-free magnetic assemblies with arbitrary 2D shapes. The quadrupole structure changes the classical magnetic particle-particle interaction in terms of both symmetry and strength. Each module has a tunable dipole moment that allows the magnetization of overall assemblies to be programmed at the single module level. We provide a simple combinatorial design method to reach both arbitrary shapes and arbitrary magnetizations concurrently. By combining modules with soft segments, we demonstrate programmable actuation of magnetic metamaterials that could be used in applications for soft robots and electromagnetic metasurfaces. Second, I will present a strategy we developed, in collaboration with researchers from the Paul Scherrer Institute, to encode multiple shape-morphing instructions into a micromachine by programming the magnetic configurations of arrays of single-domain nanomagnets on connected panels. This programming is achieved by applying a specific sequence of magnetic fields to nanomagnets with suitably tailored switching fields, and results in specific shape transformations of the customized micromachines under an applied magnetic field. Using this concept, we have built an assembly of modular units that can be programmed to morph into letters of the alphabet, and we have constructed a microscale 'bird' capable of complex behavior, including 'flapping', 'hovering', 'turning' and 'side-slipping'. These efforts establish paths forward for the creation of future intelligent microsystems that are reconfigurable and reprogrammable in situ, and that can, therefore, adapt to complex situations.

Bio: Brad Nelson has been the Professor of Robotics and Intelligent Systems at ETH Zürich since 2002. He has over thirty-five years of experience in the field of robotics and has received a number of awards in the fields of robotics, nanotechnology, and biomedicine. He serves on the advisory boards of a number of academic departments and research institutes across North America, Europe, and Asia and is on the editorial boards of several academic journals. Prof. Nelson is the Department Head of Mechanical and Process Engineering at ETH and has been the Chairman of the ETH Electron Microscopy Center and a member of the Research Council of the Swiss National Science Foundation. He also serves on boards of three Swiss companies. Before moving to Europe, Prof. Nelson worked as an engineer at Honeywell and Motorola and served as a United States Peace Corps Volunteer in Botswana, Africa. He has also been a professor at the University of Minnesota and the University of Illinois at Chicago.

Synthetic and biological magnetic microswimmers

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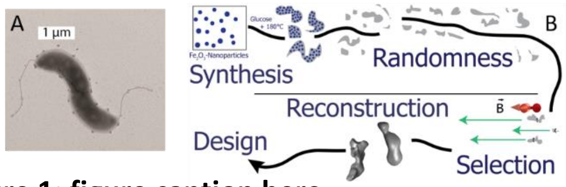
Swimming at the microscale is a difficult but essential task with implications for biological systems like bacteria as well as for synthetic microswimmers and their numerous envisioned applications[1,2].

Starting with biology, we will describe how magnetotactic bacteria avoid inefficient and long random motion thanks to magnetotaxis. These bacteria indeed mineralize magnetite nanoparticles (magnetosomes) that form an intracellular magnetic chain. Using the magnetic moment of that chain as a compass needle, they navigate along the Earth's magnetic field towards preferred physiochemical conditions. This so-called magnetotaxis is of great interest to understand the interaction between passive magnetic alignment and active swimming, which we study by connecting video-microscopy-experiments and active Brownian particle simulations [3].

Continuing with bio-inspired materials, magnetic helical propellers were designed that not only mimic the shape of bacteria flagella, but their magnetic moment also allow actuation and guidance by external magnetic fields. These artificial bacteria flagella have been studied in details over the last decade. However, it is still not clear how exactly the shape and the magnetic moment of an artificial swimmer influences their swimming behavior. Towards a better understanding of these relationships, we synthesized randomly shaped magnetic micropropellers and tested hundreds of differently shaped particles, not only for their swimming capabilities in terms of absolute velocities, but also for novel swimming behaviors that offer more flexibility than the currently considered options. We will show new strategies for designed propellers characteristics[4–7].



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Acknowledgement. This work was supported by the A*Midex foundation of the Aix-Marseille Université, the Max Planck Society and the Deutsche Forschungsgemeinschaft.

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Spontaneous oscillations, beating patterns and hydrodynamic synchronization of active microfilaments

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Cilia and flagella are ubiquitous in nature and are known to help in transport and swimming at the cellular scale by performing oscillations. Funda-mental to these periodic waveforms is the core internal structure of the filaments known as the axoneme, consisting of an array of microtubule doublets, protein linkers and dynein motors. In the presence of ATP, the collective action of the molecular motors drives internal sliding motions that are converted to spontaneous oscillations by a mechanism that still remains elusive. A sliding controlled axonemal feedback mechanism has recently been proposed and explored in the limit of small deformations, where it was shown to result in nonlinear amplitude selection through a mechanical regulation of dynein kinetics. Here, we build on that model to derive a more complete set of planar nonlinear governing equations that retains all the geometric nonlinearities, incorporates intrinsic biochemical noise and accounts for long-range, nonlocal hydrodynamic interactions [1]. For a clamped filament, motor activity drives a Hopf bifurcation leading to traveling wave solutions that propagate from tip to base, in agreement with previous weakly nonlinear studies. Quite remarkably, our results demonstrate the existence of a second transition far from equilibrium, where nonlinearities cause a reversal in the direction of wave propagation and produce a variety of waveforms that resemble the beating patterns of swimming spermatozoa. We further extend the model to account for asymmetric ciliary beats and also allow for generalized dynein regulation mechanisms that qualitatively reproduce *Chlamydomonas reinhardtii* flagellar dynamics. Our framework is used to study hydrodynamic phase synchronization in a pair of spontaneously beating filaments [2], where computations reveal that both in-phase and anti-phase synchronization are possible for asymmetric beats, while sperm-like symmetric beats always go in-phase. We also elucidate the role of biochemical noise in driving phase-slips. Our results are in agreement with recent experiments and highlight the unexplained role of molecular motors in synchronization.

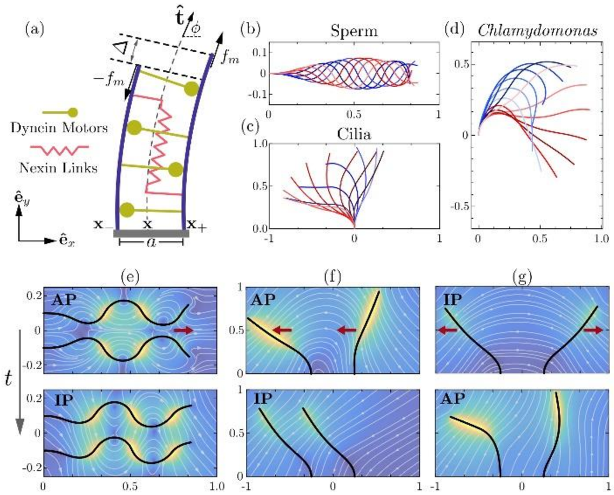

Figure 1: (a) Schematic representation of the microscopic model for the flagellar axoneme. (b)-(d) Spontaneous beating patterns emerging from the nonlinear model that approximate the waveforms of sperm, cilia and *Chlamydomonas*. (e)-(g) Synchro-nization of different beating patterns. The top panel shows snapshots at *t* = 0 and the bottom panel illustrates the final configurations. Sperms (e) beat in phase (IP), while cilia (f)-(g) can achieve either in-phase or anti-phase (AP) synchronization depending on the orientation of the power stroke indicated by red arrows. Synchronization for *Chlamydomonas* (not shown) is identical to that of cilia.

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Self-diffusiophoresis of slender cataly5c colloids

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We consider self-diffusiophoresis of axisymmetric particles using a continuum description where the interfacial chemical reaction is modeled by first-order kinetics with a prescribed axisymmetric distribution of rate-constant magnitude. We employ the standard macroscale framework where the interaction of solute molecules with the particle boundary is represented by diffusioosmotic slip.

The dimensionless problem governing the solute transport involves two parameters, the particle slenderness ε and the Damkohler number Da, as well as two arbitrary functions which describe the axial distributions of particle shape and rateconstant magnitude. The accompanying problem governing the flow about the force-free particle provides the resulting particle speed.

Motivated by experimental configurations, we employ slender-body theory to investigate the asymptotic limit $\varepsilon \ll 1$. In doing so we seek algebraically accurate approximations, where the asymptotic error is smaller than a positive power of ε. The resulting approximations are thus significantly more useful than those obtained in the conventional manner, where the asymptotic expansion is carried out in inverse powers of $\ln \varepsilon$. The price for that utility is that two linear integral equations need to be solved, one governing the axial solute-sink distribution, the other governing the axial distribution of Stokeslets. When restricting the analysis to spheroidal particles, no need arises to solve for the Stokeslet distribution. The integral equation governing the solute-sink distribution is then solved using a numerical finite difference scheme. This solution is supplemented by a large-Da asymptotic analysis, wherein a subtle non-uniformity necessitates a careful treatment of the regions near the particle ends. The simple approximations thereby obtained are in excellent agreement with the numerical solution.

Acknowledgement. This work was supported by the
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ACTIVE PARTICLES AS MOBILE MICROELECTRODES FOR LABEL-FREE CARGO TRANSPORT AND DELIVERY

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ABSTRACT

Utilization of active particles [1] to transport both biological and inorganic cargo has been widely examined in the context of applications ranging from targeted drug delivery to sample analysis. Generally, carriers are customized to load one specific target via a mechanism distinct from that driving the transport. Here, we unify these tasks and extend loading capabilities to include on-demand selection of multiple nano/micro sized targets without the need for pre-labelling or surface functionalization [2].

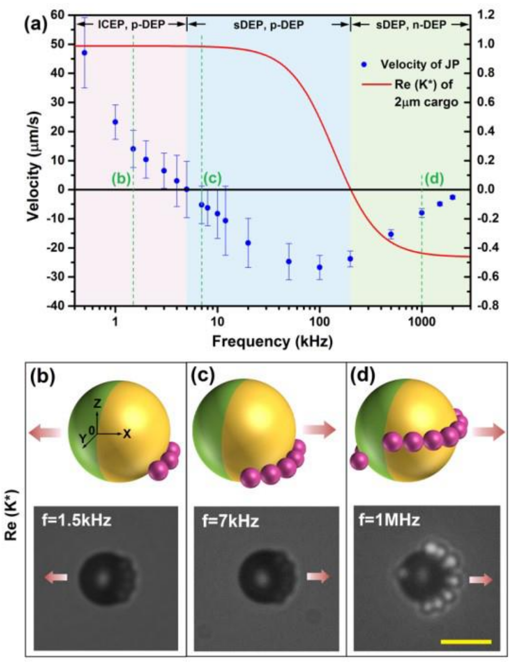

Fig.1: Cargo transport based on both positive dielectrophoresis (pDEP)and negative dielectrophoresis (nDEP) trapping.(a) For the same cargo size of 2µm we demonstrate transport of both pDEP and nDEP trapped cargo depending on the applied electric field frequency. (b) At low frequencies, the cargo particles undergo pDEP and Janus particle translates forward under induced-charge-electro-phoresis (ICEP). (c) Janus reverses direction under self-dielectrophoresis (sDEP)but cargos are still pDEP trapped. (d) nDEP trapped cargos assemble on the equator of the Janus particle.

An externally applied electric field is singularly used to drive the active cargo carrier and transform it into a mobile floating electrode that can attract or repel specific targets from its surface by dielectrophoresis; enabling dynamic control of target selection, loading and rate of transport via the electric field parameters. In expanding the frequency range of the carrier, we are able to compare the influence of different modes of carrier transport on the loading capacity as well as highlight the differences between cargo trapped by positive and negative dielectrophoresis. Adding directed motion via magnetic stirring enables to develop these active particles into in-vitro assays with single cell precision and building blocks for bottom-up fabrication. In addition, we have recently studied a new class of engineered active particles that controllably spin about their central axis in AC electric fields [3]. The rational design of these engineered particles as cargo carriers gives rise to several interesting and programmable behaviors.

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Soft hydraulics: Hydrodynamic resistances beyond Hagen–Poiseuille

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The hydraulic resistance (and laminar friction factor) of various conduits of non-circular cross-section can be obtained from exact unidirectional flow solutions of the steady Stokes equations. In the last decade, however, experiments involving internal flows in channels with a soft boundary presented surprises. The resulting soft hydraulic circuits have found numerous applications in soft robotics [1] and microfluidics [2]. Specifically, wall deformation leads to a nonlinear relationship between the volumetric flow rate and the pressure drop. Thus, the hydraulic resistance is no longer constant, rather it depends in a nontrivial way on the pressure drop. I will discuss a perturbative approach to solving soft hydraulics problems. Specifically, the Stokes equations are coupled to the equations of a linearly elasticity for the deformable wall of a microchannel or a microtube. In the distinguished limit of a long and slender geometry, the flow problem is reduced to lubrication theory. The deformation (Fig. 1) of the elastic body can likewise be reduced to a two-dimensional problem in each flow-wise cross-section. The hydrodynamic pressure provides the load, tightly coupling the fluid and elastic problems. Closed-form solutions for the deformation (either from the full elasticity problem [1] or through simplifications via plate theory [2]) allow us to determine the resistance of soft hydraulic elements, as a function of the pressure drop required to maintain steady flow and various geometric parameters, including wall thickness. Our theory compares favorably to microscale flow experiments, as well as to three-dimensional two-way coupled direct numerical simulations of fluid–structure interactions.

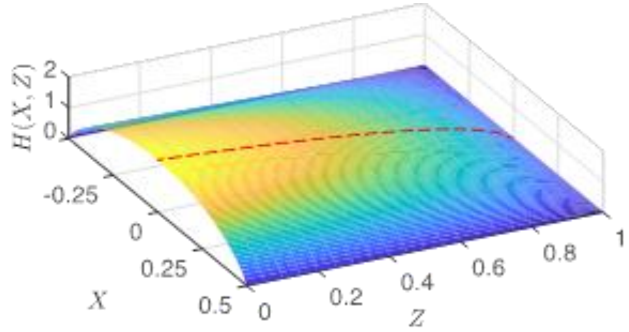

Figure 1: Predicted [3] dimensionless fluid–solid interface deflection *H*(*X*,*Z*) as a function of the cross-sectional coordinate *X* and flow-wise coordinate *Z*.

Acknowledgement. This research is supported, in part, by the U.S. National Science Foundation (NSF) under Grant CBET-1705637.

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Micromotors Go In-Vivo: From Test Tubes to Live Animals

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Nanoscale robots that can effectively convert diverse energy sources into movement and forces represent a rapidly emerging and fascinating robotic research area. Such nanoscale robots offer impressive capabilities, including greatly enhanced power and cargo-towing forces, multi-functionality, easy surface functionalization, and versatility. The new capabilities of modern nanorobots indicate immense potential for a variety of biomedical applications, and should have major impact on disease diagnosis, treatment, and prevention [1]. Recent *in vivo* applications using different types of biocompatible and biodegradable microrobots will be illustrated, including enhanced drug delivery towards enhanced treatment of stomach bacterial infection, active vaccine delivery, autonomous gastric fluid neutralization, the ability to selectively localize at desirable segments of the GI tract, or efficient intracellular delivery of functional proteins and nucleic acids.

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Hydrodynamic Centering and Symmetry Breaking in Artificial Cells

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Cell movement and intracellular transport of cellular components are dependent on the dynamic cell cytoskeleton. The Hydrodynamic interactions between cytoskeletal elements and the surrounding fluid are important for understanding the dynamics of these networks and their role in cellular positioning and movement. We focus on contracting cytoskeletal networks composed of actin filaments and myosin motors. We study these contracting actin-myosin networks in an *in vitro* experimental system based on cytoplasmic *Xenopus* egg extracts encapsulated into cell-sized water-in-oil droplets. Importantly, the presence of rapid turnover in our system allows the system to attain dynamic steady states characterized by contractile network flows which persist for hours. We find that under a broad range of conditions, the networks undergo homogenous contraction despite large spatial variations in network density.

The localization of the contraction center is size-dependent, with a symmetric configuration in larger cells and a polar one in smaller cells. In the symmetric state, the network contracts towards the center of the droplets and exhibits a spherically symmetric density and flow pattern, while in the polar state, the contraction center is localized near the droplet's boundary. During symmetry breaking, the system transitions from the symmetric state to the polar state, mimicking cellular symmetry breaking as seen for example during motility initiation or polarization of mammalian oocytes. We show that the centered state is stable against large perturbations and suggest a hydrodynamic active centering mechanism based on an imbalance of the Darcy friction forces between the contracting network and the surrounding fluid. The size-dependent localization results from a competition between the hydrodynamic centering force, and a decentering force due to transient engagement between the contracting network and the boundary, which is more prominent in smaller droplets.

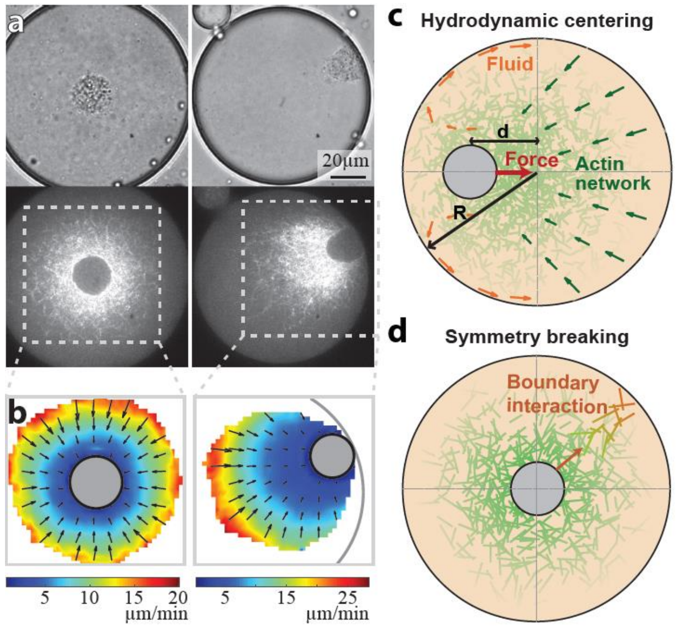

Figure 1: Centering and symmetry breaking in artificial cells. (a) Bright-field (top) and spinning disk confocal (bottom) images of a *symmetric* state with a centered aggregate (left), and a *polar* state in which the aggregate is positioned near the droplet's boundary (right). The actin network is labeled with GFP-Lifeact. The aggregate forms an exclusion zone surrounded by regions of high actin network density. (b) The network velocity field as determined by correlation analysis of the time lapse movies of symmetric and polar droplets. (c) Schematic illustration of the hydrodynamic centering mechanism. Centering arises from hydrodynamic friction between the contracting actin network and the surrounding fluid. (d) The competition between the hydrodynamic centering force and an attractive interaction with the boundary, leads to symmetry breaking.

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Optimal Actuation for Magnetic Micro-Swimmers

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Robotic micro-swimmers may have an impact in promising treatment and
diagnosis in medicine. However, efficient actuation of these robots face numerous challenges. Hence, wireless actuation is preferable over built-in actuation sources. For example, one popular strategy is the magnetization of parts of the swimmer and its actuation with an external magnetic field. In the following study, we focus on flexible magnetic micro-swimmers that are similar to spermatozoa in their design and flagellar propulsion (see Fig. 1). A numerical model is provided in order to set an automated procedure for the design of optimal actuation for flagellar magnetic Microswimmers based on numerical optimization. The numerical results are experimentally validated on a scaled-up flexible magnetic swimmer. The talk follows the work [1]. Firstly, based on the Resistive Force Theory, a simplified 3D dynamical model of a flexible swimmer has been developed generalizing the planar "N-Link" models (see [2]). By fitting the hydrodynamical and elastic parameters, we are able to obtain propulsion characteristics close to those experimentally measured. Then, we address the associated optimal control problem of finding the actuating magnetic field that maximizes the propulsion speed of the swimmer. The optimal magnetic field found via numerical optimization process are then experimentally validated. The propulsion speed of the swimmer is significantly improved using the optimal actuation. Surprisingly, the optimal trajectory of the swimmer is non-planar. This means that magnetic micro-robots swim at a maximum speed when allowed to go out-of-plane

Figure 1: The three orthogonal Helmholtz coils generate a homogeneous magnetic field in the center, where the swimmer has been placed. The swimmer is tracked using two perpendicular cameras. Shown in the corner : Scaled-up flexible magnetic swimmer used in the experiments. The tail is made of an elastomer shaped by a 3D-printed mold. The head is a magnetic disk.

Acknowledgement. This work was supported by the
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Reconfigurable Magnetic Nanoparticle-Swarm for Targeted Delivery

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Recently, untethered microrobots have drawn extensive attention due to their great potential for biomedical applications, e.g. targeted drug delivery [1-4], and sensing [4-6]. In order to enhance the loading capacity, the contrast of imaging feedback, and the access rate in complex environments, swarm behaviours at the small scales need to be studied [7,8]. Inspired by nature, large-scale robotics systems can generate complex patterns [9], however, the investigations on microrbotic swarms that are capable of performing adaptive reconfiguration and effective locomotion require further development. Moreover, as the prerequisite for their in-vivo applications, whether the microrobotic swarms can take effect in bio-fluids with complex components and different physical conditions has neither been fully investigated. Herein, we report a strategy to reconfigure paramagnetic nanoparticles into ribbon-like swarms using oscillating magnetic fields, as shown in Figure 1a. By tuning the parameters of the input fields, the microswarm can perform a reversible elongation with an extremely high aspect ratio, as well as merging and splitting behaviours, and the results are presented in Figure 1b-d, respectively. In order to understand the swarm behaviours in bio-fluids, we individually investigate the influence of fluidic viscosities, ionic strength and fibrous meshes on the swarms. Based on their performances, the optimised type of swarms in different bio-fluids is chosen based on their specific physical properties. Moreover, we also validate the analytic results by employing serum, gastric acid, blood plasma, hyaluronic acid, whole blood and vitreous humor as fluidic environments. Finally, we successfully realize the generation and navigated locomotion of microrobotic swarms in bovine eyeballs, which sheds light on the potential targeted delivery applications [10].

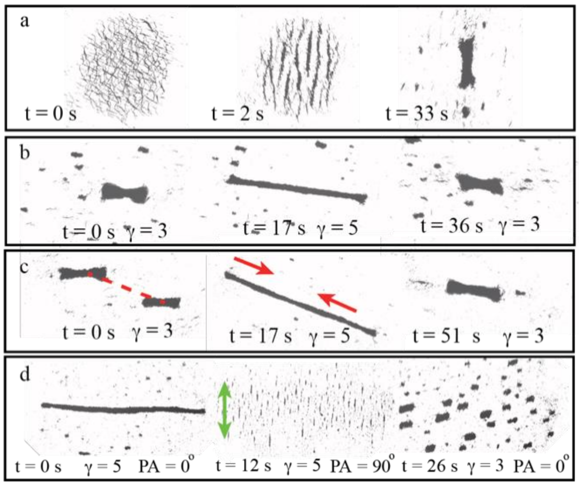

Figure 1: Ribbon-like swarm generation and pattern reconfiguration. (a) Swarm generation. Swarm pattern reconfiguration includes (b) pattern elongation, (c) contraction and (d) splitting.

Acknowledgement. This work was supported by the General Research Fund (GRF) with Project No. 14218516 from the Research Grants Council (RGC) of Hong Kong, the ITF projects with Project No. MRP/036/18X funded by the HKSAR Innovation and Technology Commission (ITC), and Project No. 3133228 from Research Sustainability of Major RGC Funding Schemes (RSFS) from CUHK.

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How Does the Choice of DNA Nanotechnology Affect the Performance of Micro-swimmers?

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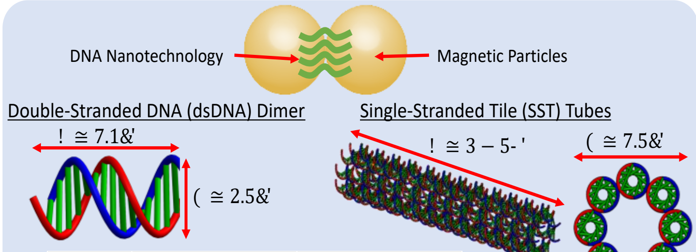
DNA nanotechnology offers interesting bottom-up, micro-manufacturing precision that is several orders of magnitude better than existing construction methods at the true micro-level (e.g., lithographic methods). This work thus asks the question: Given the ability to control aspects of "micro-assembly," how does the form of a micro-structure ultimately impact its function in a pre-defined task? To this end, this work investigates how using two different types of DNA nanotechnology to construct magnetically-actuated micro-swimmers – short (≈7nm) double-stranded DNA dimers and long (≈3-5 µ*m*) single-stranded tile tubes – affects resultant velocity when actuated by an oscillating external field. We assumed that the micro-swimmers' lengths would be independent of the type of DNA nanotechnology used, and that the "swimming direction" would be determined by the orientation of the externally applied magnetic field. Furthermore, we hypothesized that swimmers built with double-stranded DNA would have faster velocities than their single-stranded counterparts because they have lower stiffness. We tested this hypothesis by constructing micro-swimmers using both types of DNA nanotechnology. The swimmers were then placed in solution and actuated with a sinusoidally varying magnetic field. In general, we found that the micro-swimmer populations were polydisperse and that the variations in velocity data made it difficult to find clear trends. However, the data did suggest that we were correct to assume the micro-swimmer lengths were independent of the type of DNA nanotechnology used. We also found that the swimming orientation was randomly distributed, which suggests that other variables besides the externally applied magnetic field affect the orientation.



Property	dsDNA Dimer	SST Tubes
# Helices	1	8
Length	Fixed at 7.1nm	Variable from 3-5µm
Diameter	Single helix, 2.5nm	8-helix, 7.5 nm

Figure 1: DNA micro-swimmers formed using DNA micro-structures to connect magnetic particles.

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Bio-inspired Small-Scale Soft Swimmers

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Inspired by soft-bodied animals, soft functional active materials could enable physical intelligence for small-scale (from a few millimeters down to a few micrometers overall size) robots by providing them unique capabilities, such as shape changing and programming, physical adaptation, safe interaction with their environment, and multi-functional and drastically diverse dynamics. In this talk, our recent activities on design, manufacturing, and control of new bio-inspired shape-programmable active soft matter [1] and untethered soft swimmers at the milli/microscale are reported. Untethered soft millirobots inspired by spermatozoids, caterpillars, and jellyfishes are proposed using elastomeric magnetic composite materials. Static and dynamic shapes of such magnetic active soft materials are programmed using a computational design methodology. These soft robots are demonstrated to be able to have seven or more locomotion modalities (undulatory swimming, jellyfish-like swimming, water meniscus climbing, jumping, ground walking, rolling, crawling inside constrained environments, etc.) in a single robot for the first time to be able to move on complex environments, such as inside the human body [2]. Preliminary ultrasound-guided navigation of such soft robots is presented inside an *ex vivo* tissue towards their medical applications to deliver drugs and other cargo locally and heat the local tissues for hyperthermia and cauterization. Next, a more specialized soft-bodied jellyfish-inspired milliswimmer is shown to realize multiple functionalities by producing diverse controlled fluidic flows around its body using its magnetic composite elastomer lappets bent by remote magnetic fields [3]. This jellyfish robot can conduct four different robotic tasks: selectively trap and transport objects of two different sizes, burrow into granular media consisting of fine beads to either camouflage or search a target object, enhance the local mixing of two different chemicals, and generate a desired concentrated chemical path. These shape-programmable and multi-functional soft robots are aimed to be used in potential minimally invasive medical robotic applications inside the human body [4].

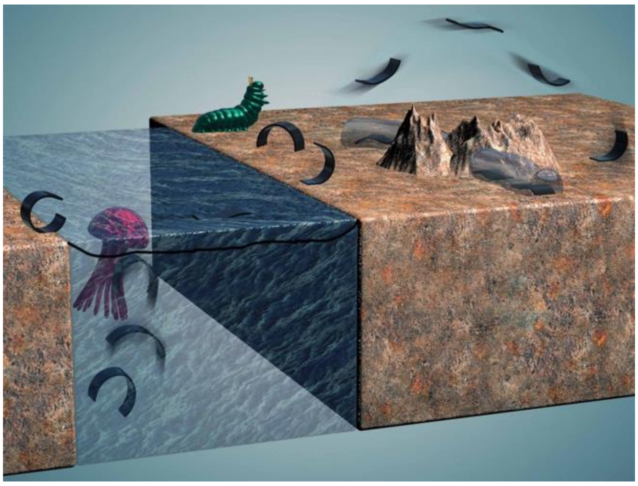

Figure 1: Bio-inspired small-scale soft-bodied magnetic robots can be remotely actuated to swim, crawl, jump, and roll in different terrains robustly and fast.

Acknowledgement. This work was supported by the Max Planck Society.

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Single Particle Propulsion using Symmetry Breaking and Flagellar Functionalization

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Abstract
Spherical microparticles in general cannot break kinematic reversibility and therefore cannot swim in low Reynolds number environments. However, both nonlinear fluid properties [1] and geometry altering surface coatings [2] can circumvent time-reversibility and enable the propulsion of symmetric geometries which would otherwise be unable to swim in Newtonian fluids. This work presents for the first time the propulsion of magnetic microparticles propelling using both a novel spontaneous symmetry breaking mechanism and through flagellar surface coatings. Magnetic microparticles suspended inside nonlinear mucus mediums were found to directionally propel using a symmetry breaking propulsion mechanism when torqued using rotating magnetic fields. This propulsion mechanism results in two symmetry broken states being produced, each with equal velocity but opposite directions. These two states can be retroactively switched between using a superimposed static magnetic field, allowing for the guided propulsion of microparticles in three dimensions. To enable propulsion in Newtonian fluids, microparticles were surface coated with bacterial flagella using an avidin biotin surface functionalization. When torqued with a rotating magnetic field, the flagella along the microparticle surface would bundle together, break kinematic reversibility, and allow for reliable propulsion in increasingly viscous fluid mediums. It was found that normal form flagella, when rotated under a counterclockwise magnetic field, microparticle propulsion was highly predictable, while clockwise rotation would sometimes generate frequency induced reversals of swimming direction; this was identified to be the result of flagellar unbundling as the microparticle rotated. Both propulsion mechanisms will be valuable in medical applications utilizing microparticles.

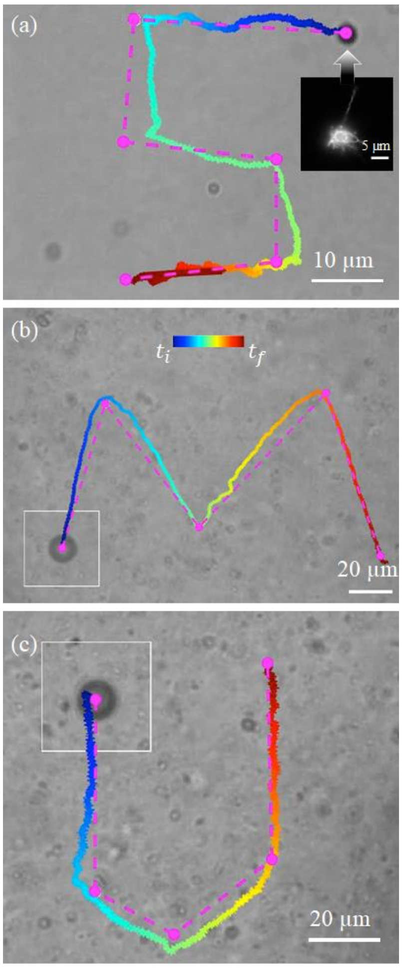

Figure 1: The closed loop feedback control of (a) Flagellated microparticle and (b-c) nonflagellated microparticles suspended within synthetic mucus. Inset of (a) shows fluorescently dyed flagella attached to a microparticle.

Acknowledgement. This work was supported by the National Science Foundation (CMMI 1712096 and .(1760642

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Dipolar Thermocapillary Motor and Swimmer

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The study of thermocapillary driven flows is typically restricted to “open” systems, i.e., ones where a liquid film is bounded on one side solely by another fluid. However, a large number of natural and engineered fluidic systems are composed of solid boundaries with only small open regions exposed to the surrounding. In this work we study the flow generated by the thermocapillary effect in a liquid film overlaid by a discontinuous solid surface. If the openings in the solid are subjected to a temperature gradient, the resulting thermocapillary flow will lead to a nonuniform pressure distribution in the film, driving flow in the rest of the system. For an infinite solid surface containing circular openings, we show that the resulting pressure distribution yields dipole flows which can be superposed to create complex flow patterns, and demonstrate how a confined dipole can act as a thermocapillary motor for driving fluids in closed microfluidic circuits. For a mobile, finite-size surface, we show that an inner temperature gradient, which can be activated by simple illumination, results in the propulsion of the surface, creating a thermocapillary surface swimmer.

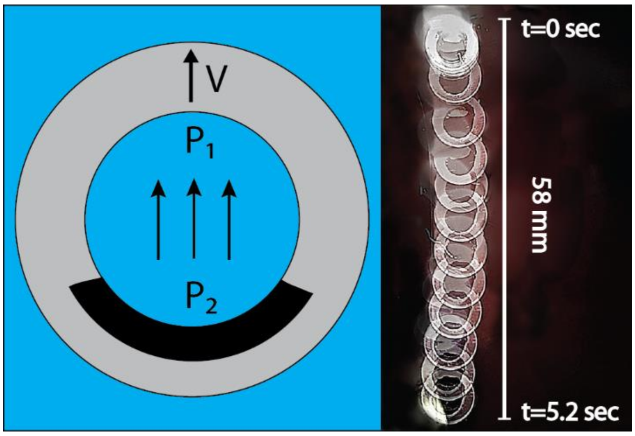

Figure 1: A circular opening in a Hele-Shaw-type confinement gives rise to thermocapillary dipole flow, which can be used to drive flow in microfluidic configurations. The same mechanism can also be leveraged for the propulsion of light-actuated surface swimmers.

Acknowledgement. This work was supported by the European Research Council (ERC), Grant Agreement No. 678734 (MetamorphChip).

Principles for Electric Field Powering, Propulsion, Actuation and Steering of Multifunctional Microdevices

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The transition from self-propelled particles to multifunctional motile microdevices requires the design of advanced particles with complex shape, structure, and internally programmed responses. Our group has investigated a broad range of principles for assembly and propulsion of responsive and active colloidal structures driven by electric and magnetic fields. Here, we will specifically discuss how AC electric fields can endow different classes of particles with the ability to move and respond in complex ways to field parameters and various stimuli. These particles use counterionic mobility to achieve directional propulsion. Typically, this requires breaking of the particle symmetry and polarization pattern, such as making metallo-dielectric particles by design [1-4]. The rich variety of mechanisms of motility in such systems include electrohydrodynamic flows, reversed electrohydrodynamic flows, induced charge electrophoresis, and self-dielectrophoresis [4]. These mechanisms will be exemplified with new classes of microspinners and particles moving by complex programmable trajectories. We will also introduce a class of active semiconductor microparticles that draw energy from external AC electric fields to self-propel in a controlled direction [1]. We developed capabilities for massively scalable production of metal/silicon particles containing microcircuits. We will show how a combination of electrokinetic effects, such as surface electroosmosis, induced charge electrophoresis, and dielectrophoresis, can controllably drive the semiconductor microdiode motion, interactions and collective dynamics, which can be triggered by the parameters of the external field or by various stimuli [5,6]. Motile silicon microcircuits can be comprehensively designed for future applications such as microsensors, artificial muscles, reconfigurable neural networks and computational systems.

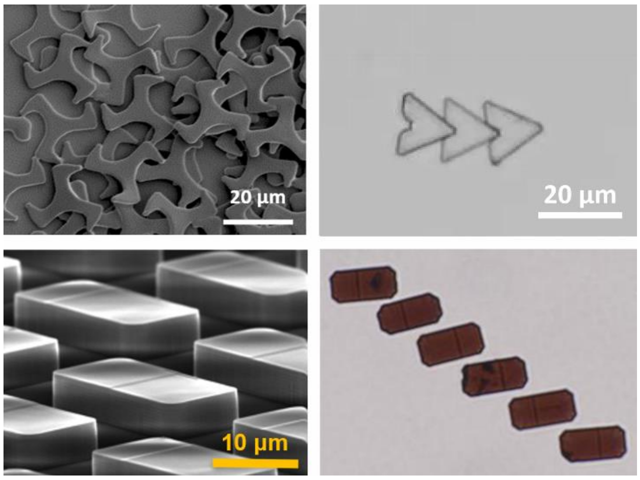

Figure 1: Examples of our electrohydrodynamics rotators, propulsors and semiconductor swimmers.

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Microswimmers and Nanopropellers Powered by Acoustic- and Magnetic-Fields

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This talk will explore the use of acoustic fields as well as magnetic fields for swimming, assembly, and robotic manipulation. While magnetic and acoustic fields are promising for untethered and *in vivo* applications, they are both difficult to shape and control locally. Recently, we have shown how one can form acoustic fields with orders of magnitude higher complexity than what has been possible before [1]. The talk will illustrate how acoustic fields can be used for micro-manipulation [2] and how one can actuate wireless robotic-arms and micro-swimmers. The dynamics of the swimmers is dependent on the Reynolds number.

Magnetic fields are also promising for wireless control of microrobots [3]. Here, it is more challenging to obtain spatial control of the field. The actuation therefore depends largely on the shape and magnetic properties of the micro-robotic agent, including its symmetry [4]. Also, the local chemistry must be considered, for instance to realize transport through real organs and tissue [5].

Despite recent progress in the field, there are still several challenges for micro-swimmers and small-scale actuators, in particular:

- Transfer of power and force to small scales
- Actuation of swarms
- Biocompatibility
- Tissue penetration
- *In vivo* operation
- Imaging and tracking.

In our research we addressing these challenges, and this talk will present our results and work on manipulating micro-swimmer and –robots using acoustic and magnetic fields.

Acknowledgement. The research was in part supported by the European Research Council under the ERC Advanced Grant Agreement HOLOMAN (no. 788296), by the Univ. of Stuttgart and by the Max Planck Society.

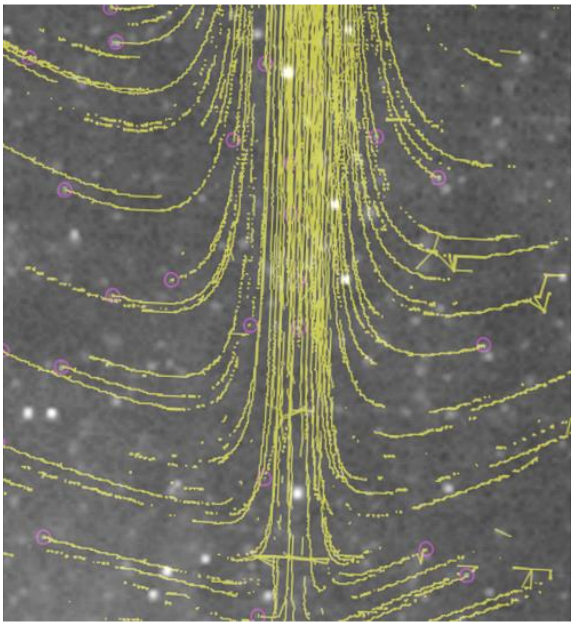

Figure 1: Particle tracking shows jetting that occurs under acoustic streaming at high frequency. The recoil force can be used to drive a wireless actuator.

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Novel Fluids in Soft Robot Fluidic Elastomer Actuators

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(i) Independent Control over Variable Compliance and Shape Change, and (ii) High Energy Density via Liquid Batteries

Fluidic actuators are excellent at providing (i) shape change and (ii) variable compliance in soft robots. These two variables, however, are not independently controllable. In this talk, I will present a new class of granular fluids for the independent control of shape change and variable compliance. We demonstrate the benefit of this concept in a catcher’s mitt for grabbing a dropped ball. Further, we also have replaced hydraulic fluid in soft actuators with a Zinc Iodide half flow-cell battery to create a swimming soft robot that can operate for nearly 40 hours. The analysis of the capabitilities and the details of the system development will be discussed, as well as future directions for these new abilities.

Adding Soft Materials to Robots at Small Scales

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Multimaterial mechanisms are seen throughout natural organisms across all length scales. The different materials in their bodies, from rigid, structural materials to soft, elastic materials, enable mobility in complex environments. As robots leave the lab and begin to move in real environments, including a range of materials in 3D robotics mechanisms can help robots handle uncertainty and lessen control requirements. For the smallest robots, soft materials combined with rigid materials can facilitate large motions in compact spaces due to the increased compliance. Materials can also be used to embed control into the mechanics of a robot at small scales. However, integrating various material components in 3D at the microscale is a challenge.

This talk will focus on two aspects of this work. First, we present an approach for 3D microscale multimaterial fabrication using two-photon polymerization. Two materials with three orders of magnitude difference in Young's moduli are printed in consecutive cycles (Figure 1). Integrating a soft elastic material along with a rigid material has enabled the formation of hybrid elements, strongly adhered together, with layer accuracy below 3-µm
resolution.

In addition, we show that using soft viscoelastic materials in the legs of small robots results in high speed, stable running from an open-loop control strategy. By changing the material choice, and therefore compliance and damping, we show the trade-offs inherent in performance goals such as speed, efficiency, and stability. We demonstrate experimental results from quadrupedal gram-scale robots running at speeds up to 11.7 body lengths per second (Figure 2).

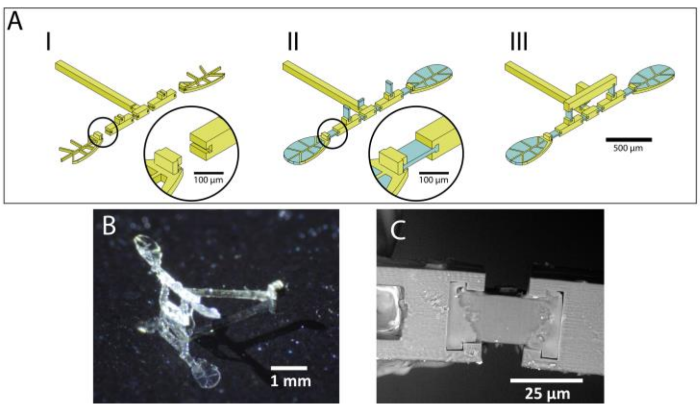

Figure 1. A 2-mm wingspan flapping wing mechanism with flexible joints printed with both rigid and soft materials using two-photon polymerization.

Acknowledgement. This work was supported by the Israeli Ministry of Defense (Contract No. 4440767595)
and the National Science Foundation (Award No. ECCS1055675).

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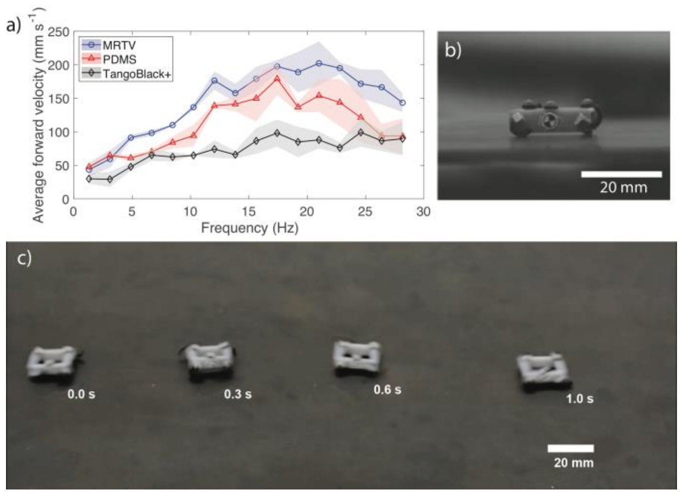

Figure 2. Experimental locomotion data from magnetically actuated, gram-scale quadrupedal robot using different viscoelastic leg materials.

New 3D and 4D printing materials for soft robotics

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Abstract

Additive manufacturing, which is fabrication through material deposition processes, brings new opportunities in utilization of printing technologies, beyond the field of conventional graphics. New materials and processes for 3D and 4D printing will be introduced, for fabrication of objects composed of shape memory polymers, elastomers and hydrogels. Examples of applications of these materials will be presented, in fabrication of responsive objects and actuators that can change shape and move upon external triggering. Demonstrations in soft robotics will include three-layer actuators composed of carbon nanotubes and shape memory polymers, pH responsive hydrogels, magnetically driven actuators, dynamic jewellery and medical devices.

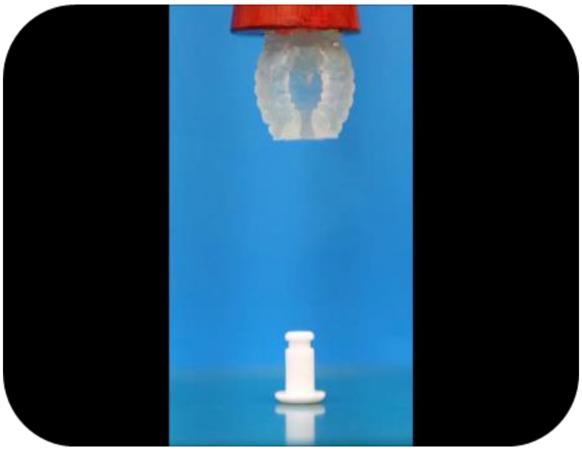

Figure 1: 3D printed gripper composed of stretchable polymers

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Dynamics of model snakes and elastic sheets

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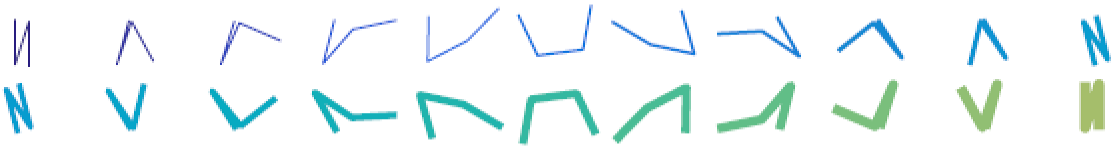

Figure 1: Sliding locomotion of a three-link body under isotropic Coulomb friction.

We address two topics related to locomotion and soft robotics. The first is the sliding locomotion of model snakes. Snakes' bodies are covered in scales that make friction anisotropic, and allow for sliding locomotion with an undulatory gait, for example. Isotropic friction is a simpler situation (that arises with snake robots, for example) but is less understood. Using modeling and computations we find that simple undulatory motions give little net locomotion in the isotropic regime. We compute time-harmonic motions of three-link bodies and find that local optima for efficiency involve static friction to some extent. We then propose a class of smooth body motions that have similarities to concertina locomotion and can achieve optimal efficiency for both isotropic and anisotropic friction.

Recent applications (e.g. active gels and self-assembly of elastic sheets) motivate the need to efficiently simulate the dynamics of thin elastic sheets. We present semi-implicit time stepping algorithms to improve the time step constraints that arise in explicit methods while avoiding much of the complexity of fully-implicit approaches. For a triangular lattice discretization, our semi-implicit approach is stable for all time steps. For a more general finite-difference formulation the analogous approach is stable for time steps two to three orders of magnitude greater than for an explicit scheme. We study a model problem with a radial traveling wave form of the sheet's reference metric, and find transitions from quasi-periodic to chaotic dynamics as the sheet thickness is reduced, wave amplitude is increased, and a damping constant is reduced.

Acknowledgement. This work was supported by the NSF Mathematical Biology program under Award No. DMS-1811889 and by the Michigan Institute for Computational Discovery and Engineering (MICDE).

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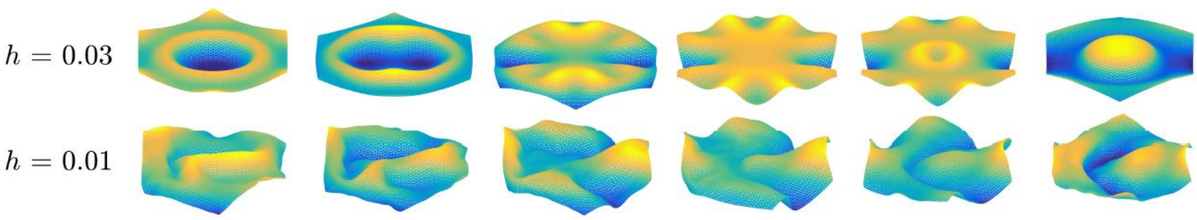

Figure 2: Elastic sheet dynamics with a periodic radial traveling wave form of the reference metric, and thicknesses h = 0.03 (top) and 0.01 (bottom).

Asymptotic analysis and optimal control of periodic inputs for microswimmers locomotion

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Many robotic systems use internal periodic shape changes (gaits) that, coupled with the interaction with the robot's environment, create locomotion. Prominent examples of such systems with two shape variables are the low Reynolds 3-link "Purcell swimmer" with inputs of 2 joint angles [1] and the "ideal fluid" inertial swimmer [2]. Gait optimization of these locomoting robots is of high importance, and has been studied mainly using numerical methods. Using the variational optimal control approach of "Pontryagin's maximum principle" (PMP) for these swimmer models enables finding displacement-optimal gaits for certain swimmer's geometries [3], but diverges for others. In an attempt to better understand the optimal gaits and explain the divergence, we examine another method for calculating optimal gaits, namely geometric optimal control.

Ramasamy and Hatton [4] use differential geometry to calculate the curvature of the local connection (its total Lie bracket) for 3-link swimmers. Using optimized choice of coordinates, the net displacement of a gait is obtained as the area integral of the curvature over the region enclosed by the gait. Thus, contour plots of the curvature in shape space (fig 1) gives visualization that enables identifying distance-optimal gaits. By analyzing contour plots for the different swimmer geometries, we find that in some cases, junctions appear in the zero-level curves, which explain the failure of the PMP method since there is no single solution to the optimal control problem. Further comparison between the two methods may help in finding gaits for maximal efficiency for these systems and others.

In another work [5], we study energy-optimal gaits for multi-link microswimmers under prescribed displacement per cycle. Using leading-order analysis assuming small joint angles' amplitudes, the constrained variational formulation leads to an eigenvalue problem. The solution for optimal gaits is obtained as travelling waves which form a planar elliptic loops in the space of N-1 joint angles.

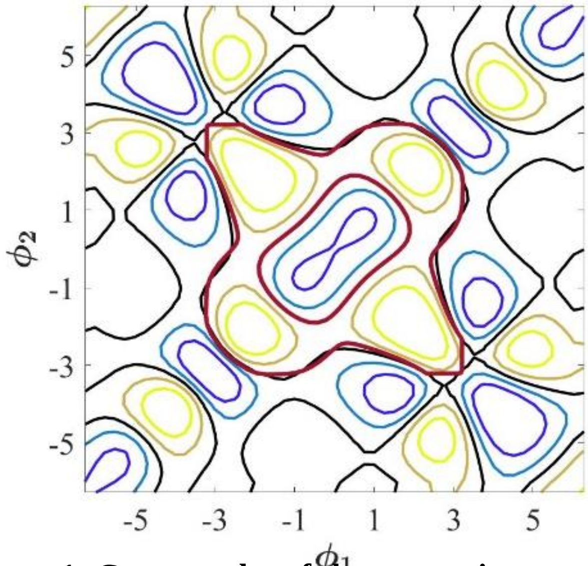

Figure 1: Contour plot of the connection curvature for Purcell's 3-link swimmer. Zero-level curves are in black. Optimal gait found using PMP with bounds are in red.

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Clément Moreau

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Gouri Patil

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Ido Levin

Luca Berti

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Controllability of Magnetized Purcell's Swimmers

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This talk will focus on the control theory aspects of the dynamics of micro-swimmer robot models made of two or three rigid segments, linked together with torsional springs. The swimmers are magnetized and driven with a uniform, time-varying magnetic field. Under generic assumptions on the parameters, we show that the control system which describes the swimmers' dynamics is locally controllable in small time around its equilibrium position (the straight line), but with bounded controls that do not go to zero as the target state gets closer to the initial state. Moreover, the controls have to remain close to a constant value depending on the swimmer's parameters, that can be obtained by computing Lie brackets of interest associated to the control system. We additionally illustrate our result with numerical simulations. This result gives an insight on the propulsion strategies at micro-scale, and provides better understanding of this type of two-control systems.

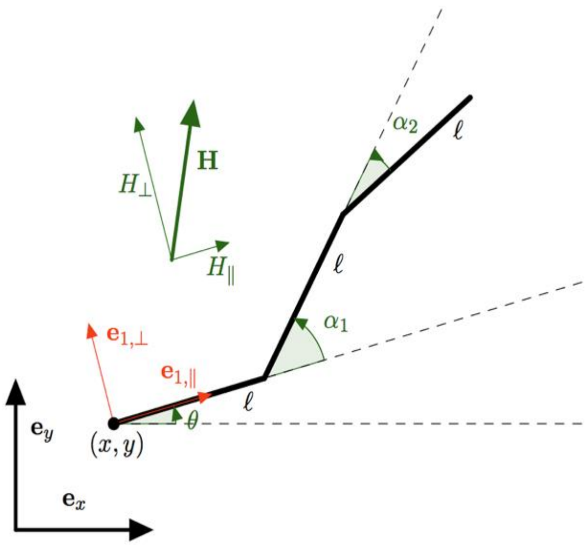

Figure 1: 3-link microswimmer model

Acknowledgement. This work was done with the help and supervision of Laetitia Giraldi (Inria), Pierre Lissy (Univ. Paris-Dauphine) and Jean-Baptiste Pomet (Inria).

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Locomotion Model of a Miniature Undulating Robot Crawling, In A Flexible Environment

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Bioinspired crawling robots have been the topic of numerous studies in the last few decades. Their applications range from pipe maintenance to crawling inside the biological vessels of the body. In these applications the robots need to crawl over anisotropic and flexible terrains with varying surface properties and respond with flexibility to different coefficients of friction and dimensions. One of the most common approaches to robot design is the minimalistic approach; i.e., a small number of motors and actuators.

This research presents the design, manufacturing and analysis of a miniature wave-producing robot named SAW – a Single Actuator Wave robot, which is destined to be used as a self-propelled probe of the intestines, for medical diagnostic inside the digestive system.

We present the mechanical design of the miniature model of the robot, its structure and main components. The mechanical design of SAW is simple and based on a rotating helix and a series of links attached using R joints. The robot is actuated using a DC motor, which rotates the helix, and the links attached in series produce the advancing wave motion during the actuation of the robot. The length of the robot is 63 mm, its maximum width is 15 mm and it weighs only 3.4 g including the motor (see Figure 1).

Next, we present two locomotion models we developed to characterize the cases where the robot is crawling between two straight surfaces or over a single flat surface. For each case, we specified the conditions in which the robot will advance and the advance time ratio as a function of the friction forces, structural parameters and the weight of the robot.

Additionally, we present a computer simulation that demonstrates the robot's advancing-sliding locomotion over a single flat surface. The simulation also allows the optimization of different structural parameters of the robot.

Finally, we describe the design and manufacturing of multiple experimental systems, including synthetic tube-like compliant surfaces and forces measuring device, which we created to test the robot's motion and analyze the forces acting on it inside compliant tubes. Using the forces measuring device, we verified the ability of the robot to advance inside a tube in different conditions. Furthermore, we performed multiple experiments both inside the flexible tubes and in pig's intestines, which proved the capability of the robot to advance inside these challenging environments.

Keywords: Wave robot, Wave locomotion, Medical robot, Endoscopy, Compliant surfaces.

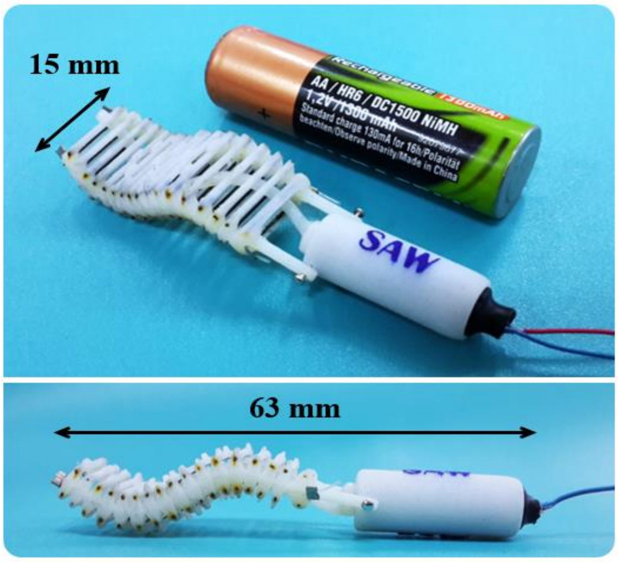

Figure 1: The miniature SAW robot

References.

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Nanorobots as sensors for cancer microenvironment

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Abstract

Malignant cancer cells constantly interact with their surrounding environment and migrate by remodeling the local extracellular matrix (ECM)[1,2]. A quantitative understanding of the remodeled ECM can provide new insights into the process of metastasis. Cells suspended in 3D matrices can mimic many of the physicochemical and mechanical properties of tumors in vivo. Our system is designed to approximate the in vivo histopathological milieu of a malignant breast tumor[3]. Nanorobots can be effective tools for studying cellular biophysics[4] and probing the local rheology of biological systems[5]. Here we demonstrate how magnetically actuated helical nanorobots can probe a 3D tissue co-culture consisting of both cancerous and non-cancerous cells. We find that nanorobots adhere preferentially near cancer cells due to the distinct charge conditions of the cancer-sculpted ECM. The spatial extent of the remodeled ECM was measured to be approximately 40 µm for all cells. However, quantitative measurements showed the adhesive force to increase with metastatic ability of the cell lines. We hypothesized and experimentally confirmed that specific sialic acid linkages related to cancer-secreted ECM may be a major contributing factor in determining this adhesive behavior. Cell-line specific anisotropy in sialic acid distribution was also discovered by nanorobots. These findings can lead to promising applications in cancer diagnosis and quantification of cancer aggression.

Acknowledgement. This research was supported in part by DBT and DST. DDG and DP will like to thank IISc and the Ministry of Human Resource Development (MHRD), Government of India for providing the Senior Research Fellowship (SRF). RB would like to acknowledge support from the SERB ECR Grant (1586), Wellcome Trust-DBT India Alliance Fellowship (WELT0041), and the DBT-IISc partnership program (BT/PR27952/INF/22/212/2018).

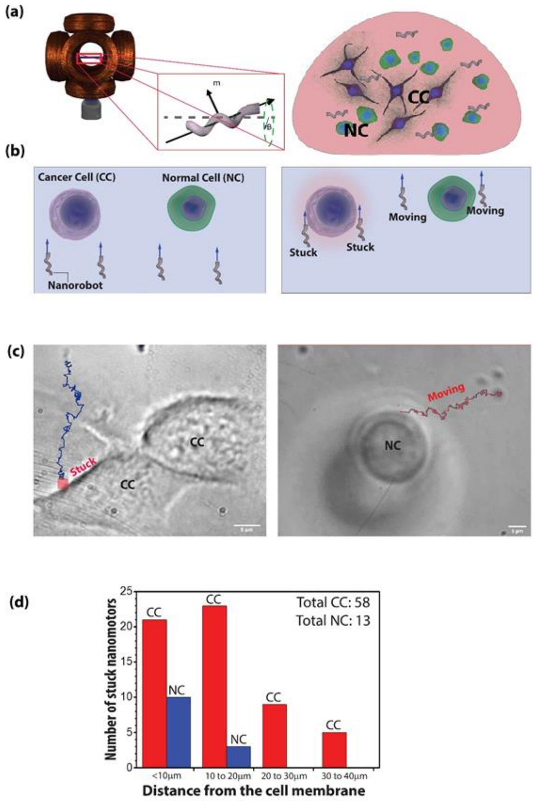

Figure 1: (a)Schematic representation of the experimental system containing the heterogenous 3D culture, placed within a triaxial Helmholtz coil built around a fluorescence microscope and the schematic of nanorobots with magnetic material embedded inside the helix. (Right panel) Schematic of the 3D co-culture containing cancer cells (labelled as CC, purple), non-transformed cells (labelled NC, green) and helical nanorobots. (b): Schematic representation of experimental procedure where nanorobots are magnetically maneuvered within the 3D co-culture. We find the nanorobots to be preferentially adhered to the ECM near the CC. (c) Experimental trajectory of a nanorobot approaching a CC and a NC. A nanorobot approaching CC gets adhered in the ECM close to the cell as shown in the left panel. However, as shown in the right panel, a nanorobot starting from the vicinity of a NC can be maneuvered away without adhering. (d) The graph shows the number of adhered nanorobots as a function of distance from the cell surface from NC and CC. Only cells with nanorobots in their surroundings were recorded for this graph.

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Printed flexible actuators for soft robotics

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Printed flexible actuators, key components in soft robotics, are enabling delicate movements with simple mechanism. The main challenge is to achieve devices that are able to perform large and significant movements, towards fabrication of a soft walking robot.

Electro-thermal actuators, a common type of flexible actuators, are bi-layer structures in which the movement is caused due to differences in thermal expansion coefficients between the two layers. In carbon nanotubes (CNT) based actuators, one of the layers, the electrode layer, is composed of CNTs which functions as an electrical heater and the other composed of a flexible polymer.

Herein, this study presents new three layered structured electro-thermal actuators that perform large movements, while combining polymers with various mechanical properties, including shape memory polymers that enable out-of-the-plain movements. The effect of the third polymeric layer thickness and stiffness, on the movement of the actuator is studied and actuators with unique shapes are presented.

In addition, the study is focused on fabrication of 3D printed ferrofluid-based actuators, where the actuation is by a magnetic field. The effect of the ferrofluid flow and the mechanical properties of the polymeric materials on the obtained movement is studied. Actuators mimicking a human hand and a worm (figure 1) are demonstrated.

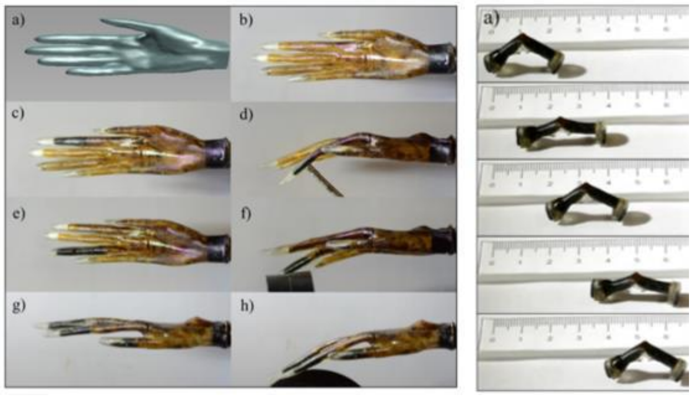

Figure 1: a 3D printed ferrofluid based "hand" (left) and "worm" (right) like actuators. (ref. 2)

Acknowledgement. This research was partially supported by the Singapore National Research Foundation under the CREATE program: Nanomaterials for Energy and Water-Energy Nexus and by the Israeli Ministry of Defense (IMOD).

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Magnetic active matter based on helical propulsion.

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Nanomotors provide a promising route toward the study of complex active matter phenomena with a well-defined and possibly reduced set of variables. The motivation stems from the prevalence of self-powered systems in nature, ranging from intracellular transport to human migration, which are non-equilibrium phenomena yet to be completely understood. Among different ways of powering nanomotors, magnetic field deserves a special mention because of its inherent biocompatibility, minimal dependence on properties of the surrounding medium, and remote powering mechanism. The magnetically actuated propellers (MAPs), which are helical structures driven by rotating fields can be modeled as active particles by changing the mode of actuation to oscillating magnetic fields. This technique induces motility in the form of back-and-forth motion but allows the directionality to be unspecified, and therefore, represents a zero-force, zero-torque active matter. The MAPs show enhanced diffusivity compared with their passive counterparts, which depends on the thermal noise as well as the inherent asymmetries of the individual motors and their motility can be tuned by altering the external magnetic drive. We further discuss the collective behaviour of such systems including their diffusivity enhancement effects on passive tracers akin to the measurements done in bacterial suspension. Apart from this, the experimental challenges of large-scale fabrication of swimmers with narrow range of magnetic and geometric characteristics and custom-made actuation set-up is also discussed. Finally, we envision this new model system to play a vital role in investigating fundamentals of swarming/flocking phenomena and develop intelligent, multi-functional nano-swimmers for biomedical practices.

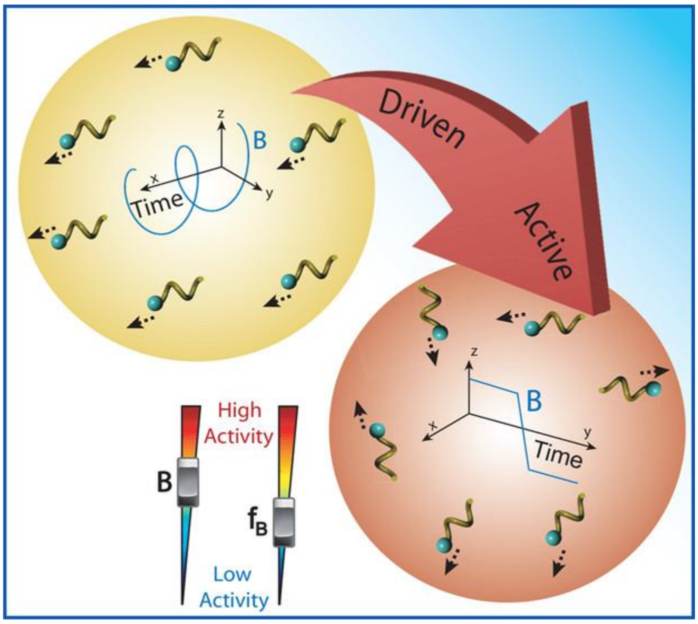

Figure 1: From driven to active system by changing the mode of actuation. Tuning of activity is simply by playing around with magnetic field and frequency.

Acknowledgement. We acknowledge the funding from RGUHS, DBT and also MHRD,MeitY,DST nanomission for supporting fabrication facilities at CeNSE,IISc.

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Design of a cable-actuated soft hand rehabilitation device for patients with neurological disorders

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Recently, many cable-driven soft robotic gloves have been developed for compact and light weight design [1]. However, the finger and thumb motion of most of these devices are limited to simultaneous flexion and extension of finger/thumb joints that limits achievable grasping tasks. Also, when these devices are applied to patients with neurological disorders, conventional extensor design with a single cable along the dorsal aspect of the finger often produce non-physiological finger motions (i.e., hyperextension of the distal interphalangeal joint or metacarpophalangeal joint) due to the abnormal passive impedance of the joints. In this study, we introduce a novel dexterous soft robotic glove that could be tuned for individuals to provide 'subject-specific' assistance to achieve various motions physiologically. The structure and orientation of the extrinsic and intrinsic tendons of the human finger were replicated with elastic materials (silicon) and actuated cables to achieve physiological motions. In order to achieve various grasping tasks such as palmer pinch and lateral grasp, two degrees of freedom of the thumb (flexion/extension and opposition/reposition) were actively assisted. The finger and thumb extensors of the device were composed of elastic materials that provide passive extension assistance (Figure 1a). The flexor tendons, intrinsic tendon of the finger, and the tendon for thumb opposition were actively assisted with actuated cables (Figure 1b). Various grasping motions were achievable with the dexterous thumb, and the spatiotemporal coordination of non-physiological finger/thumb extension caused by various types of impairments could be enhanced by adjusting the assisted forces of the extrinsic and intrinsic tendons [2].

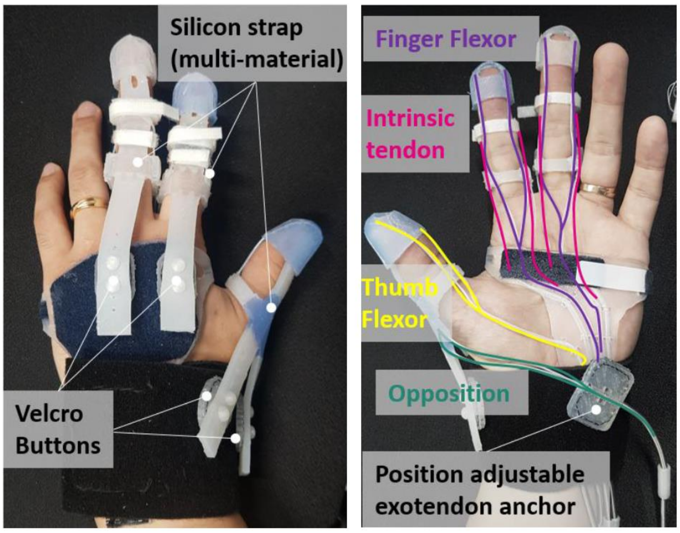

Figure 1: Overview of the device (left: dorsal view; right: palmer view)

Acknowledgement. This paper is based on a research which has been conducted as part of KAIST-funded Global Singularity Research Program for 2019.

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Self-Powered Non-Euclidean Plates

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Abstract

Imposing residual stresses on thin structures is an established mechanism to induce global shape changes. Living organism have mastered the dynamic control of these residual stresses to induce shape changes and locomotion. By comparison, man-made implementations are rudimentary. Here we present the first autonomously shape-shifting soft sheets and show that these have the potential to achieve the locomotive capabilities of living organisms. The sheets are made of a gel that shrinks and swells in response to the phase of an oscillatory chemical (Belousov-Zhabotinsky) reaction. Propagating reaction-diffusion waves of the reaction induce localized shrinking or swelling of the gel resulting in time-periodic global shape changes, for example flapping. We present the computational tools and experimental protocols needed to control this system, principally the relationship between curvature of the sheet and the reaction phase, and optical imprinting of the wave pattern. This quantitative control marks an important step towards the realization of autonomous soft machines.

Reference IL, R. Deegan, E. Sharon, **2019**, *ArXiv:1906.00386*

Optimal shape for multi-flagellated micro-swimmers

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In this talk we focus on the shape optimisation of multi-flagellated micro-swimmers. The starting geometry is the one of Magnetococcus-Ovoid (MO-1) bacterium [1-2]: its shape is modelled by juxtaposing an ellipsoidal head and two helicoidal tails [3] (see Fig.1), while its propulsion strategy is simulated by rotating its tails around the respective axes. Our study aims to improve the average advancement speed of the swimmer by optimising the geometry of its shape.

This talk is divided in two parts.

In the first part we deal with the mathematical modeling of the problem. Stokes equations are chosen to model the fluid flow, since the swimmer is assumed to be microscopic and the Reynolds number very low. Numerical simulations are performed via the Boundary Element Method, using the MATLAB library *Gypsilab* [4].

In the second part of the talk, we present the results of the optimisation under fixed tail length. Firstly, a mono-flagellated micro-swimmer is considered. Optimal helix radius and wavelength are larger than those reported in [3] and the optimal head is elongated in the propulsion direction. An analysis of the tail section confirms experimental findings (ISIR-UPMC by the group of Stéphane Régnier) about larger propulsion speeds for polygonal geometries. Secondly, the bi-flagellated swimmer is addressed. In this case, optimal helix radius and wavelength are even larger, and the optimal head shape depends on angles α and γ. Thirdly, a four-tailed swimmer is optimised. Surprisingly, we found its swimming speed to be comparable, if not lower, to the bi-flagellated one's.

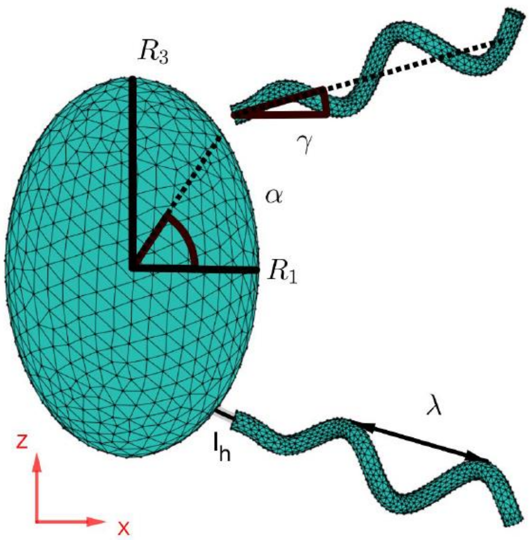

Figure 1: Model for the MO-1 bacterium.

Acknowledgement. This work was supported by the CNRS Defi Infiniti C.O.M.M. project and the Labex IRMIA PhD scholarship.

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“Scalloping” with friends

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Inertialess hydrodynamics is notorious for its time-reversibility constraints. Reciprocal motion is unable to produce net propulsion, as per the celebrated *Scallop Theorem*: a scallop, composed of two rigid rods hinged at one extremity, cannot go anywhere in an inertialess fluid by performing a periodic motion. In nature, microorganisms exploit a variety of swimming strategies to break time-reversibility in the system. Elasticity is more commonly used to achieve this goal, as seen during spermatozoa swimming or ciliary beating.

Breaking the time-reversibility constraint with rigid arms is more challenging; one way is to increase the degrees of freedom of the swimmer (its shape parameters), as seen for Purcell’s three-link swimmer. Another way is to increase the number of swimmers: two scallops swimming together can in fact produce net propulsion. In this case, non-local hydrodynamic interactions induce an unequal distribution of momentum on each swimmer in such a way that time-reversibility of the ensemble is broken, thus both scallops are able to swim despite their individual reciprocal motion. In this work, we explore the controllability of two inherently non-controllable units by exploiting the non-local nature of their mutual interaction.

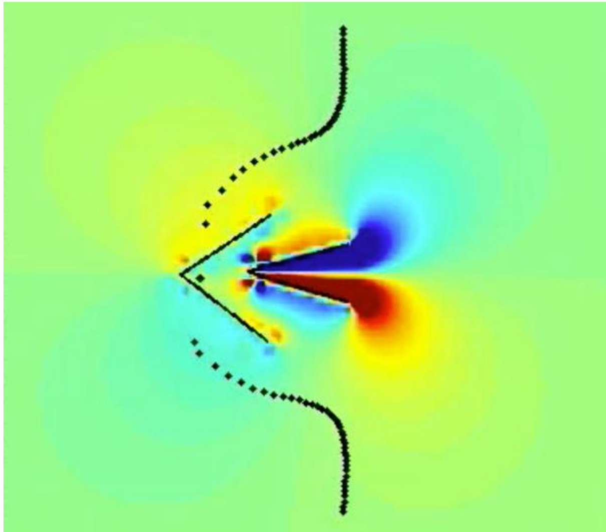

Figure 1: Two two-link swimmers moving together. Source: Les Houches School of Physics, France, 2009.

The Effect of Connections between Fluid-Filled Cavities on Cellular Metamaterials and Soft Robotics

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The study of elastic structures embedded with fluid-filled cavities received considerable attention in fields such as smart materials, sensors, actuators and soft-robotics. This work studies an elastic beam embedded with a set of fluid-filled bladders, similar to a honeycomb structure, which are interconnected via an array of slender tubes. The configuration of the connecting tubes is arbitrary, and each tube may connect any two bladders. Beam deformation both creates, and is induced by, the internal viscous flow- and pressure-fields which deform the bladders and thus the surrounding solid. Applying concepts from poroelasticity, and leveraging Cosserat beam large-deformation models, we obtain a set of three coupled equations relating the fluidic pressure within the bladders to the large transverse and longitudinal displacements of the beam. We show that by changing the viscous resistance of the connecting tubes we are able to modify the amplitude of oscillatory deformation modes created due to external excitations on the structure. In addition, rearranging tube configuration in a given bladder system is shown to add an additional degree of control, and generate varying mode shapes for the same external excitation. The presented modified Cosserat model is applied to analyze a previously suggested energy harvester configuration and estimate the efficiency of such a device. The results of this work are validated by a transient three-dimensional numerical study of the full fluid-structure-interaction problem. The presented model allows for the analysis and design of soft smart-metamaterials with unique mechanical properties.

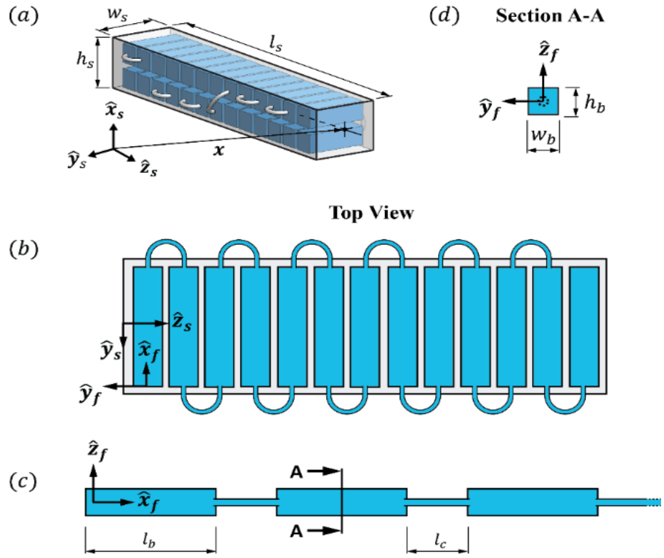

FIG. 1. Illustration of a solid-liquid composite beam structure with interconnected bladder array. *(a) Elastic beam with various connections between bladders, lab frame* $(\hat{\mathbf{x}}_s, \hat{\mathbf{y}}_s, \hat{\mathbf{z}}_s)$ *and position vector* $\mathbf{x}$ *pointing to material point along the reference curve (neutral axis). (b) Top view of a serpentine configuration and fluidic curvilinear frame* $(\hat{\mathbf{x}}_f, \hat{\mathbf{y}}_f, \hat{\mathbf{z}}_f)$*. (c) Mapping of the bladder and tubes into a straight continuous channel. (d) Definition of bladder cross section at rest (A-A).*

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Slender phoretic filaments: theory and control capabilities.

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Artificial microswimmers are a new technology with promising microfluidics and biomedical applications, such as directed cargo transport, microscale assembly, and targeted drug delivery.

Fuel-based microswimmers, such as autophoretic Janus particles, self-propel by generating concentration gradients in a surrounding solute. These are simple to manufacture and do not require specialised equipment, however offer very limited control capabilities. Classical designs of Janus particles, in the shape of a sphere or straight rod, lack control as the trajectory is not user defined, posing a fundamental barrier in realising their potential applications.

A novel design, microtranformers, overcome this limitation using shape changing phoretic filaments that enable precision navigation. Switching between U and S shapes that give rise to the basic swimming modes of translation and rotation, can be achieved using flexible, thermoresponsive filaments that change shape according to a user-controlled stimulus [1].

In order to efficiently model such swimmers, we develop a Slender Phoretic Theory (SPT) for the chemohydro- dynamics of microscale autophoretic filaments of arbitrary centreline, as a one- dimensional substitute for inefficient numerical solution of 3D partial differential equations. We show that, unlike other slender body theories, azimuthal effects that appear at first order for curved shapes have a leading order contribution to the swimming kinematics, and consider the effects of curvature for U-, S- and helical filament shapes [2].

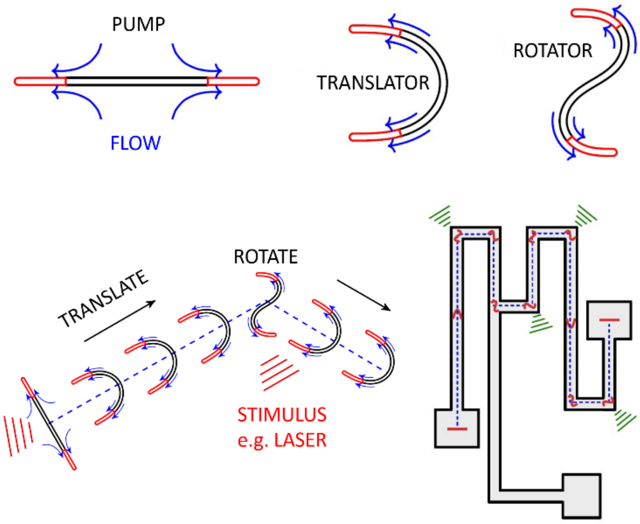

Figure: Flexible phoretic filaments can achieve precise, user-defined navigation by switching between the basic swimming modes of translator (U-shaped) and rotator (S-shaped) according to an external stimulus such as ultrasound.

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Untethered Shape-changing elastomer via liquid-gas phase transition

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We study how the liquid-gas phase transition of liquid drops in an elastomer matrix may be used to design a reversible shape-changing material.

We use droplets of alcohol trapped in an elastomer matrix, and when this composite material is heated, the liquid boils inside the cavities, leading to a rise of the inner pressure and to the global expansion of the material. This action is reversible because the matrix is elastic and the pressure is released when the liquid goes back to its initial state, if temperature is lowered[1].

The goal is then to design objects that can evolve from a planar sheet to controlled 3D shapes. This property could be used in soft robotics to design robots than can deform continuously. Our sample can adopt curvature in two directions, because we use in-plane metric deformation[2]. The strategy selected here is to favor some directions of heat-induced expansion. In order to block or favor some directions of deformation a network of small thin branches cut out of a mylar sheet is embedded inside the elastomer matrix. Meshes are designed to have soft modes, allowing deformation only along some selected directions. Depending on the privileged direction of expansion (radial or orthoradial), we show how to program the final shape of the material as a saddle or a cone shape. We also report how different patterns can be used for the mesh, such as oriented chevrons or diamond shapes, and we show that specified shapes can be obtained through the design of the meshes.

Figure 1: Thermic shape changing

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Morphing soft-robotic aircraft skins

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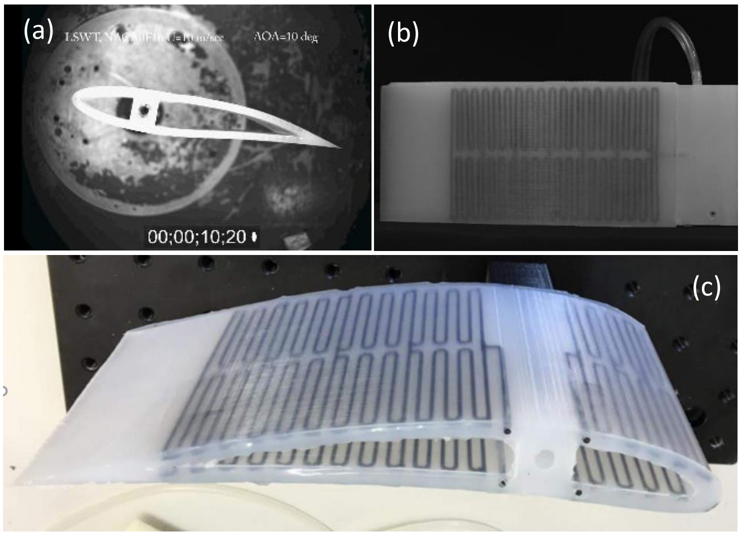
Current aircraft wings are designed to passively limit wing deformation due to aerodynamic loads. Limiting wing deformation requires a sufficiently rigid, and thus heavier wing structure. Modification of wing aerodynamic properties as required of conventional rigid aircraft necessitates the creation of geometrical discontinuities (via flaps, ailerons, etc.). The discontinuities associated with standard flight control surfaces increase drag, noise and fuel consumption. Several approaches have been taken to attempt to reduce the required rigidity of aircraft structures. Such is the case with active aeroelasticity [1], where the aim is to use aerodynamic forces as restoring rather than add mass and rigidity to counteract them. The current approach employs internal pressurized channel actuation as a mechanism for active wing section camber manipulation. The advantages of this approach are the ability to continuously modify the camber, in a flapless configuration, as well as reduce aerodynamic forces and moments by achieving a balance between internal wing pressures and external aerodynamic forces [2].

The study presents a method for actively modifying aircraft wing section cambers. Based on an internal pressurized channel network embedded within the wing (see figure), a flapless configuration may be achieved in which cambers are exchanged rather than discontinued with mechanically complex lifting devices. We employ current soft-robotic approaches and the EPN (Embedded Peeling Network) model and demonstrate the feasibility of the suggested configuration in a low speed wind tunnel test.



Wind tunnel testing of the NACA0F16 airfoil.
(a) Top view of the airfoil at 10 [m/sec], Re = $0.5*10^6$ and -10 [deg] angle of attack with active upper-camber pressurization – high speed camera image.
(b) Side view of the airfoil, EPN channels are visible in black, pressure lines enter the airfoil top-right.
(c) The NACAF6412 morphing airfoil wind-tunnel prototype with integral camber EPN channels.

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Hyper Redundant Articulated Robot for NDT of Close Complex Structures

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The robotic system in this paper is designed for NDT, Not Destructive Testing, of closed and complex structures. The robotic system will be hyper redundant, articulated and snake-like. The robotic system can be divided into two main sub-systems. First is the base of the robot which include the actuators. This sub-system is stationary and doesn't enters the tested structure. It contains several linear actuators, each actuator connected to a single string. This string goes through the robot links, and by its end connected to one of the links. The second sub-system is the robot's links, the links are mainly hollow and chained to each other and can revolve respectively to each other, like a robotic arm but with greater number of links (10+). By pulling or releasing the strings using the linear actuators we can rotate the links in their axis. Each DOF of the robot's links will be controlled by two strings attached to linear actuators.

This mechanism will allow the snake-like robot to be lightweight and have very small diameter (~65 mm) because it mainly hollow, and we can chain links to make it longer (~2.5 meter). Moreover, the robot will be able to pass through the cramped narrow passages inside the structures to perform tasks like taking pictures, 3D mapping, or scan for structural defects using ultrasonic sensors. Another advantage is its ability to take any shape and curvature to navigate inside the structure without leaning or using the structure itself.

Two of the major developments are motion control system and motion planning system of hyper redundant articulated robots.

Figure 1: Robot links

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Micromotor-Based Biosensing via Label-Free Transport of Functionalized Beads

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The reliable identification of the target analytes using lab-on-a-chip technology promises an enormous potential in the fields of environmental monitoring, food testing, food/water safety monitoring, and clinical analysis.[1] In particular, the emerging field of self-propelling (i.e. "active" particles) combined with microfluidics offers new opportunities for realization of novel micromotor-based biosensing. Garcia et al[2] demonstrated a micromotor-based immunoassay using self-propelled antibody-functionalized micromotors where the different immunoassay steps are obtained via the mobile particle translating between different reservoirs connected using microfluidic channels. This concept eliminates the need to manipulate fluids as common to lab-on-a-chip devices where the washing step is obtained by the motion of the particle within stagnant fluid. However, the coating of the active particle with antibodies make these micromotor specific and less generic. Here, we demonstrate a generic approach using a non-labeled micromotor that can selectively load, transport and release cargo (functionalized beads) singularly controlled by an external alternating electric field. The underlying mechanism of the cargo manipulation was dielectrohporesis (DEP) which enabled label-free loading and release of beads by simply tuning the frequency.[3] As a proof of concept for immunoassay, we used a simplified model of fluorescent tagged avidin molecules in conjunction with biotin-coated microparticles. The multiples operation steps (binding, wash) were successfully demonstrated in a controllable and reversible manner, which includes 1) cargo transporting of biotin-coated particle into a avidin reservoir, 2) transporting avidin-bound biotin-particle to an avidin-free reservoir and direct visualization.

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Inflatable Shape Morphing Simply via Zigzags

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Zigzags structures can be found in a wide variety of fields. For instance, the future leaves of hornbeam are folded in the buds into zigzagging features that deploy as the leaves grow. This natural example has been the source of inspiration to develop origami designs [1]. Here, we present a novel strategy where inextensible thin patches are sealed along zigzag paths to generate complex shape transformation under applied pressure [2].

We investigate the change in metrics induced by the inflation of these paths and the consequent transformation of the initially flat patches into 3D structures. In particular, we studied in detail the case of asymmetric zigzags, which leads to a rotation of the deformation tensor and widens the routes for reverse-engineering. We finally propose a theoretical model based of zigzagging paths to program the deployment of flat sheets into 3D shapes [3].

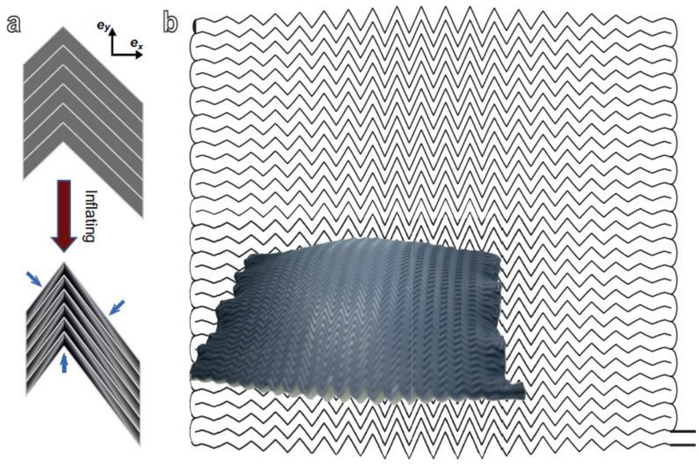

Figure 1: Flat inflatables with Zigzag pattern. (a) Illustration of the deformation progress under applied pressure; (b) Photograph of an experimental realization of curled surface when inflating using the background Zigzag pattern

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Analysis of Cargo Loading Modes and Capacity of an Electrically-Powered Active Carrier

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The use of active colloids for cargo transport offers unique potential for applications ranging from targeted drug delivery to lab-on-a-chip systems. Previously, Janus particles (JPs), acting as mobile microelectrodes have been shown to transport cargo which is trapped by a dielectrophoretic mechanism [1]. Herein, we aim to characterize the cargo loading properties of mobile Janus carriers, across a broad range of frequencies and voltages (Experimental setup see Figure 1(a)). In expanding the frequency range of the carrier, we are able to compare the influence of different modes of carrier transport on the loading capacity as well as highlight the differences between cargo trapped by positive and negative dielectrophoresis (See Figure 1(b)). The results are supported by a COMSOL simulation (see Figure.1 (c)). Specifically it is shown that cargo trapping results in a reduction in carrier velocities with this effect more ronounced at low frequencies where cargo is trapped close to the substrate. Interestingly, we observe the existence of a maximum cargo loading capacity, which decreases at large voltages suggesting a strong interplay between trapping and hydrodynamic shear. Finally, we demonstrate that control of the frequency can enable different assemblies of binary colloidal solutions on the JP. The resultant findings enable the optimization of electrokinetic cargo transport and its selective application to a broad range of targets.

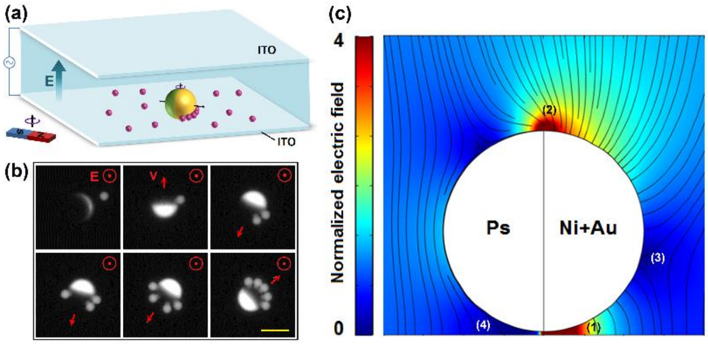

Figure.1: Experimental setup and methodology. (a) Schematics of the microchamber including the JP carrier and the trapped 2μm cargo particles. The magnetic field is used for steering of the JP via the ferromagnetic Ni coating while the electric field is used for both propulsion and cargo manipulation; (b) Using magnetic steering for individual pickup of 3μm cargo in order to study the velocity of the carrier as a function of the number of cargo. AC voltage of 5V and 1.5MHz is applied. The direction of the JP velocity is indicated with red arrows. The scale bar is 10μm; (c) Numerical simulation results showing the electric field distribution around the JP that is in vicinity to the powered electrode and the corresponding locations where positive (locations 1 and 2) and negative (locations 3 and 4) DEP trapping of cargo can occur.

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