The Belfer Memorial Symposium on Microswimmers

Monday, January 12th, 2015

Faculty of Mechanical Engineering, Technion

Auditorium 1 Floor 0, Dan Kahn Building

Organizer: Yizhar Or, Technion

Program:

08:30 - 09:00	Registration and coffee		
09:00 - 09:20	**Opening**		
	Session 1 - Biological microswimmers. Chair: Shimon Haber		
09:20 - 10:10	**Keynote 1 - Eric Lauga**	Cambridge, UK	The hydrodynamics of locomotion in non-Newtonian fluids
10:10 - 10:40	Paulo Arratia	Upenn	Motility Behavior of Escherichia coli in dilute polymer suspensions
10:40 - 11:05	Alex Leshansky	Technion	Undulatory locomotion of finite filaments: lessons from C. elegans
11:05 - 11:30	Gregory Zilman	Tel Aviv U.	The hydrodynamics of contact of a marine larva, *Bugula neritina* , with a cylinder
11:30 - 12:00	Peer Fischer	Max Planck Inst.	Dynamics and control of micro- and nanoswimmers in complex biological fluids
12:00 - 12:30	MinJun Kim	Drexel Univ.	Gangnam style in microbiorobotics: Biologically inspired microscale robotic sytems
12:30 - 14:00	Lunch break - Coler Visitor Center		
	Session 2 - Robotic microswimmers. Chair: Alex Leshansky		
14:00 - 14:50	**Keynote 2 - Brad Nelson**	ETH	Swimming Microrobots
14:50 - 15:15	Emiliya Gutman & Yizhar Or	Technion	Simple model of a planar undulating magnetic microswimmer
15:15 - 15:40	Shimon Haber	Technion	Swimmers utilizing surface traveling waves: Analytical and experimental study
15:40 - 16:05	Konstantin Morozov	Technion	Orientation and propulsion of chiral nanomotors
16:05 - 16:35	Coffee break		
	Session 3 - Other microswimmers. Chair: Gilad Yossifon		
16:35 - 17:00	Gabor Kosa	Tel Aviv U.	Comparative study of actuation methods for robotic microswimmers
17:00 - 17:25	Alicia Boymelgreen, G. Yossifon & T. Miloh	Technion & TAU	Spinning Janus doublets driven in uniform AC electric fields
17:25 - 17:50	Yossi Avron	Technion	Quantum swimmers in Fermi sea
17:50 - 18:15	Ehud Yariv	Technion	Osmotic self-propulsion of rod-shaped particles
18:15 - 18:25	**Closing**		

Technion—Israel Institute of Technology

Faculty of Mechanical Engineering

The 28th James (Jimmy) H. Belfer symposium

on

Microswimmers

Organizer: Yizhar Or

Technion, Faculty of Mechanical Engineering

Audorium 1, Floor 0, Dan Kahn Building

January 12, 2015

In Memory of James H. Belfer

The symposium on “Microswimmers” is dedicated to the late James (Jimmy) H. Belfer and is organized by the Faculty of Mechanical Engineering at the Technion, Israel Institute of Technology.

Jimmy Belfer was an exceptional young man, intelligent, kind, sensitive and possessed a fine sense of humor. He was a loving and beloved son to his parents and a treasured brother to his two young sisters and older brother. Jimmy was only 20 years old when, on August 28, 1976, he was swimming in a reservoir in Colorado when a drunken, hit-and-run boat driver careened out of control into the designated swimming area causing the tragic and untimely loss of Jimmy's life.

Jimmy, whose father is a survivor of the holocaust, grew up in a home strongly committed to the State of Israel and the Jewish People. He loved Israel and his visit there at the age of 15 intensified his admiration, concern and love for the country – so much that when Yom Kippur war broke out, he asked his parents to let him to go to Israel to assist in any possible manner.

Having the tragic and agonizing responsibility of commemorating the name and memory of their son and brother, his parents, brother and sisters have endowed the Technion`s James (Jimmy) Hugh Belfer Chair in Mechanical Engineering and the James (Jimmy) Hugh Belfer Symposium Fund. This choice was predicated on Jimmy`s love for Israel, and his keen interest in all things mechanical.

May his soul rest in peace.

List of James H. Belfer Symposia

No.	Subject	Date	Organizer(s)
1.	*Heat Transfer in the Living Body and its Environment*	15.6.1989	A. Shitzer
2.	*Artificial Hands for Robotics and Rehabilitation*	18.12.1991	Y. Mizrahi M. Shoham
3.	*Computational Fluid Dynamics*	9.6.1993	D. Degani
4.	*Modeling of Structures and Mechanical Systems*	8-10.5.1995	Y. Ben-Haim
5.	*Recent Developments in Cryosurgery*	24.5.1995	A. Shitzer
6.	*Nonlinear Systems*	12.6.1996	M. B. Rubin
7.	*Nonlinear Mechanics*	16.6.1997	A. Oron
8.	*Heat and Mass Transfer within the Living Body and with its Environment*	1.4.1998	A. Shitzer
9.	*Computer-Aided Surgery, Medical Robotics and Medical Imaging*	4.5.1998	M. Shoham
10.	*Nonlinear Mechanics*	26.10.1998	M. Shapiro
11.	*Computer-Aided Surgery, Medical Robotics and Medical Imaging*	18.5.2000	M. Shoham
12.	*Nonlinear Mechanics*	11.6.2000	M. B. Rubin E. Tadmor
13.	*MEMS (micro-electro-mechanical-systems) Day in Israel*	15.11.2001	G. Grossman M. Lifshitz Y. Nemirovsky
14.	*Measurements and Uncertainty Evaluation in Coordinate Measuring Machines an Scanners and their Implication on Design and Reverse Engineering*	29-30.11.2004	A. Fischer M. Shpitalni
15.	*New Technologies and Visualization Methods for Product Development in Design and Reverse Engineering*	6-7.11.2005	A. Fischer M. Hee Kim S. Park A. Shamir
16.	*Control of the Indoor Air Quality for Improving Human Well Being, Comfort and Productivity*	7.11.2005	A. Shitzer

17.	*Cryogenic Engineering and Applications*	4.4.2006	G.Grossman B-Z.Maytal
18.	*Nonlinear Mechanics*	12.6.2006	O. Gottlieb
19.	*Aerosols - Environment, Measurement and Health*	19.12.2006	M. Shapiro D. Broday
20.	*Nano-Bio Mechanics Workshop*	17-18.12.2008	E. Zussman H.D. Wagner
21.	*Neuro-Mechanics, Dynamics and Decision Making*	15-16.2.2009	M. Zacksenhouse
22.	*Medical and Biomedical Applications of Thermal and Non-Thermal Processes*	27.4.2010	A. Shitzer Y. Halevi
23.	*Atmospheric Aerosols*	23.2.2011	D. Broday M. Shapiro
24.	*Structural Dynamics Systems - Design, Control and Energy Harvesting*	29.2.12	I. Bucher Y. Halevi
25.	*Risk Assessment of Nuclear Accidents*	29.10.2012	E. Elias M. Shapiro
26.	*Decisions Under Severe Uncertainty*	21.1.2013	Y. Ben-Haim I. Erev
27.	*Nonlinear Wave Phenomena: From weak nonlinearity to sonic vacuum*	13.1.2014	Y. Starosvetsky O. Gendelman

The 28th James H. Belfer (Jimmy) symposium
Microswimmers

Program:

08:30 – 09:00	**Registration and coffee**
09:00 – 09:20	Opening: Yoram Halevi, Dean of Mechanical Engineering & Belfer Chair; Yizhar Or, Conference Organizer
	Session I: Biological Microswimmers (Chair: Shimon Haber)
09:20 – 10:10	***Keynote Lecture 1:*** **Eric Lauga**, *Department of Applied Mathematics and Theoretical Physics, University of Cambridge, UK* ***The locomotion of microbes in non-Newtonian fluids***
10:10 – 10:40	Alison E. Koser, Arvind Gopinath, and Paulo E. Arratia, *Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania* ***Motility Behavior of Escherichia coli in dilute polymer suspensions***
10:40 – 11:05	Alexander Leshansky, *Faculty of Chemical Engineering, Technion* Undulatory locomotion of finite filaments: lessons from C. elegans
11:05 – 11:30	Gregory Zilman, *School of Mechanical Engineering, Tel Aviv University* ***The hydrodynamics of contact of a marine larva, Bugula neritina, with a cylinder***
11:30 – 12:00	Peer Fischer, *Max Planck Institute for Intelligent Systems* ***Dynamics and control of micro- and nanoswimmers in complex biological fluids***
12:00 – 12:30	MinJun Kim, *Department of Mechanical Engineering & Mechanics, Drexel University* ***Gangnam style in microbiorobotics: Biologically inspired microscale robotic sytems***
12:30 – 14:00	**Lunch break**
	Session II: Robotic Microswimmers (Chair: Alex Leshansky)
14:00 – 14:50	***Keynote Lecture 2:*** **Bradley Nelson**, *Department of Mechanical and Process Engineering, ETH Zurich* ***Swimming Microrobots***
14:50 – 15:15	Emiliya Gutman & Yizhar Or, *Faculty of Mechanical Engineering, Technion* ***Simple model of a planar undulating magnetic microswimmer***
15:15 – 15:40	Shimon Haber, *Faculty of Mechanical Engineering, Technion* ***Swimmers utilizing surface traveling waves: Analytical and experimental study***
15:40 – 16:05	Konstantin Morozov, *Faculty of Chemical Engineering, Technion* ***Orientation and propulsion of chiral nanomotors***
16:05 – 16:35	**Coffee break**
	Session III: Other Microswimmers (Chair: Gilad Yossifon)
16:35 - 17:00	Gábor Kósa, *School of Mechanical Engineering, Tel Aviv University* ***Comparative study of actuation methods for robotic microswimmers***
17:00 - 17:25	Alicia Boymelgreen , Gilad Yossifon & T. Miloh, *Department of Mechanical Engineering, Technion* ***Spinning Janus doublets driven in uniform AC electric fields***
17:25 - 17:50	Joseph Avron, *Faculty of Physics, Technion* ***Quantum swimmers in Fermi sea***
17:50 - 18:15	Ehud Yariv, *Department of Mathematics, Technion* ***Osmotic self-propulsion of rod-shaped particles***
18:15 - 18:25	Closing: Yizhar Or, Conference Organizer

Book of Abstracts

Keynote Lecture 1:

The locomotion of microbes in non-Newtonian fluids

Eric Lauga

Department of Applied Mathematics and Theoretical Physics, University of Cambridge, UK

Many microbes (for ex. bacteria or green algae) possess flagella, slender whiplike appendages which are actuated in a periodic fashion in fluids and allow the cells to self-propel. The biological fluids encountered by these microorganisms can display complex microstructures and rheology. Motivated by recent experiments, we consider the problem of microbial locomotion in complex, non-Newtonian fluids. While past theoretical work seems to indicate that viscoelasticity should systematically hinder locomotion, experimental observations suggest that locomotion enhancement is possible. In this talk, we first present an overview of our experimental results on the topic (collaboration with Roberto Zenit, UNAM, Mexico). We then propose two physical mechanisms leading to enhanced swimming, which we quantify mathematically. We finally demonstrate how to asymptotically derive integral theorems relating the arbitrary motion of an isolated organism to its swimming kinematics in a non-Newtonian fluid.

Bio:

Eric Lauga is a Senior Lecturer at the University of Cambridge and Trinity College, UK, since 2013. He earned his Bachelor degree at Ecole Polytechnique (1998), MS degree at the University of Paris VI (2001) and PhD at Harvard (2005). He has been an Assistant Professor at MIT and Associate Professor at U.C. San Diego. Eric's research expertise is in theoretical fluid mechanics, and particularly its application to biological physics and fluid locomotion at the micro-scale. He has been granted several teaching and research awards, including NSF Career Award. He serves as Associate Editor in Physics of Fluids, European Physical Journal E, and Journal of Fluids and Structures.

Keynote Lecture 2:

Swimming Microrobots

Bradley Nelson

Department of Mechanical and Process Engineering, ETH Zurich, Switzerland

Nature has inspired numerous microrobotic locomotion designs that are suitable for propulsion generation at low Reynolds numbers. This talk first reviews various swimming methods with a particular focus on helical propulsion inspired by *E. coli* bacteria. To actuate swimming microrobots, various magnetic actuation methods have been proposed, such as rotating fields, oscillating fields, and field gradients. These methods can be categorized into force-driven or torque-driven actuation. It can be shown that torque-driven approaches scale better to the micro- and nano-scale than force-driven approaches. The implementation of swarm or multi-agent control will also be discussed. The use of multiple microrobots may be beneficial for *in vivo* as well as *in vitro* applications, and the frequency-dependent behavior of helical microrobots allows individual agents to be decoupled from within small groups. Finally, an elegant commercial application of microrobots originally inspired by helical swimmers will be presented.

Bio:

Brad Nelson has been the Professor of Robotics and Intelligent Systems at ETH Zürich since 2002. He has thirty years of experience in the field of robotics and has received a number of awards for his work in 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 has been the Department Head of Mechanical and Process Engineering at ETH, Chairman of the ETH Electron Microscopy Center, and is a member of the Research Council of the Swiss National Science Foundation. He is a member of the board of directors 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.

Motility Behavior of *Escherichia coli* in dilute polymer suspensions

Alison E. Koser, Arvind Gopinath, and Paulo E. Arratia

Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, USA

The run-and-tumble dynamics of *E. coli* in Newtonian fluids has been extensively studied. However, outside the laboratory, *E. coli* is known to live in many complex media including biological fluids in the digestive system and soils. Here, we experimentally investigate the motility behavior of *E. coli* in dilute polymeric solutions using particle-tracking methods. We find that the addition of small amount of polymer to water drastically changes the run-and-tumble behavior of *E. coli* cells, enhancing translation while hindering rotational diffusion. Here, the cells are suspended in dilute solutions of carboxy-methyl cellulose of different molecular weights and are imaged far from any surfaces. Results show that the average velocity of the cells increases as the polymer concentration (and viscosity) increases. Furthermore, we find that the addition of polymer to the fluid leads to cell trajectories that are highly correlated in time; that is, cells move in nearly-straight lines and rotational diffusion is greatly reduced. Our experiments show that this combination of increased speed and suppressed reorientation dramatically changes overall cell dynamics in the presence of polymers.

Undulatory locomotion of finite filaments: lessons from C. elegans

Alexander Leshansky

Faculty of Chemical Engineering, Technion - Israel Institute of Technology, Israel

Undulatory swimming is a common propulsion strategy adopted by many small organisms including various single-cell eukaryotes and nematodes. In this work, we report a comprehensive theoretical study of undulatory locomotion of a finite filament using (i) approximate resistive force theory (RFT) assuming a local nature of hydrodynamic interaction between the filament and the surrounding viscous liquid, and (ii) particle-based numerical computations taking into account the intra-filament hydrodynamic interaction. Using the ubiquitous model of a propagating sinusoidal waveform, we identify the limit of applicability of the RFT and determine the optimal propulsion gait in terms of (i) swimming distance per period of undulation and (ii) hydrodynamic propulsion efficiency. The occurrence of the optimal swimming gait maximizing hydrodynamic efficiency at finite wavelength in particle-based computations diverges from the prediction of the RFT. To compare the model swimmer powered by sine wave undulations to biological undulatory swimmers, we apply the particle-based approach to study locomotion of the model organism nematode C. elegans using the swimming gait extracted from experiments. The analysis reveals that even though the amplitude and the wavenumber of undulations are similar to those determined for the best performing sinusoidal swimmer, C. elegans overperforms the latter in terms of both displacement and hydrodynamic efficiency. Further comparison with other undulatory microorganisms reveals that many adopt waveforms with characteristics similar to the optimal model swimmer, yet biological swimmers still manage to beat the best performing sine-wave swimmer in terms of distance covered per period. Overall our results underline the importance of further waveform optimization, as periodic undulations adopted by C. elegans and other organisms deviate considerably from a model sine wave.

Hydrodynamics of contact of self-propelled marine invertebrate larvae *Bugula Neritina* with a cylindrical collector: Theory and experiment

Yulia Novak and Gregory Zilman

School of Mechanical Engineering, Tel Aviv University

Settlement of a marine invertebrate larva on a body collector implies its contact with the collector. Given that velocities of sea currents are much larger than swimming velocities of marine larvae, larval motion toward a collector is generally regarded as transport of passive particles. However, the collision efficiency of small particles with a large collector is extremely low. Can weak self-propulsion increase the probability of a larva-swimmer to make contact with a collector?

We recorded trajectories of *Bugula neritina* larvae and trajectories of polystyrene beads in the velocity field of a vertical cylinder. By considering a larva as a self-propelled mechanical microswimmer, we formulated a mathematical model of its motion in the shear flow induced by the collector. Simulated larval trajectories were compared with experimental observations.

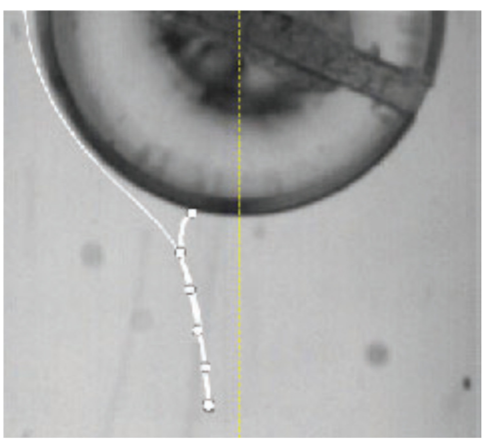

Figure 1. Trajectories of *B. Neritina* larva (line with circles) and beads (solid line).

Using Monte-Carlo simulations, we found that the probability of contact of a self-propelled larva with a collector may be orders of magnitude larger than the corresponding probability of contact of a passive particle. To continue its life history a marine larva must settle. The results of our investigation imply that using self-propulsion, a larva may increase it odds to make contact with a collector and, thus, to survive.

Dynamics and control of micro- and nano-swimmers in biological fluids

Peer Fischer

Max Planck Institute for Intelligent Systems, Germany

To build, power, and operate structures that can navigate complex fluidic environments at the sub-mm scale is challenging. Moving through fluid environments at the scale of micro-organisms presents a different set of challenges compared to those encountered by macroscopic swimmers, and these are in general exacerbated when the medium is a complex biological medium. I present recent results where the locomotion of colloidal nanopropellers benefits from the complex rheology of ubiquitous biological fluids and media [1]. Although strong Brownian forces dominate in water we achieve controlled propulsion of the nanopropellers in biological gels, which paves the way for applications inside biological media and the extracellular matrix. These constitute some of the smallest nanorobotic systems that have been realized to date [1]. Finally, I show that it also possible to benefit from the non-Newtonian and viscoelastic properties of complex biological fluids. Unlike water, these media allow a reciprocal swimmer to swim at low Reynolds number. We have recently implemented these ideas in a microscallop that swims in hyaluronic acid solutions [2] – despite the scallop theorem suggesting that it does not move in water.

[1] "Nano-Propellers and their Actuation in Complex Viscoelastic Media", D. Schamel, A.G. Mark, J.G. Gibb, C. Miksch, K.I. Morozov, A.M. Leshansky, P. Fischer, ACS Nano 8, 8794 (2014).

[2] Swimming by Reciprocal Motion at Low Reynolds Number", T. Qiu, T.-C. Lee, A. G. Mark, K. I. Morozov, R. Münster, O. Mierka, S. Turek, A. M. Leshansky, P. Fischer, Nature Comm. 5 5119 (2014).

Gangnam style in microbiorobotics: Biologically inspired microscale robotic sytems

MinJun Kim

Department of Mechanical Engineering & Mechanics, Drexel University, USA

One of the challenges in microrobotics is to find suitable and simplistic ways to swim in low Reynolds number. For such work, magnetically controlled achiral microswimmers with the simplest possible body structures were shown to swim in low Reynolds number environment. Most previous works on artificial microswimmers had always focused on using chiral or flexible structures to generate non-reciprocal swimming motions in low Reynolds numbers; this inevitably brings complicity to the swimmers' shapes and structures. However, an achiral and rigid structure can swim under the proper conditions, as demonstrated by this work. An achiral microswimmer consists of three magnetic micro-particles conjugated through avidin-biotin chemistry and magnetic self-assembly. A magnetic control system of approximate Helmholtz coils was used to control the microswimmers. Both directional and velocity control were successfully implemented to navigate the swimmers through low Reynolds number environment. Furthermore, multi-robot manipulation, modular robot control, and PIV characterization had been employed. The implication of the swimming phenomenon and the robust control demonstrated herein serves as great potential to revision future developments of microrobots, especially for therapeutic targeting and minimally invasive surgical procedures.

Simple model of a planar undulating magnetic microswimmer

Emiliya Gutman and Yizhar Or

Faculty of Mechanical Engineering, Technion - Israel Institute of Technology, Israel

One of the most efficient actuation methods of robotic microswimmers for biomedical applications is by applying time-varying external magnetic fields. In order to improve the design of the swimmer and optimize its performance, one needs to develop simple theoretical models that enable explicit analysis of the swimmer's dynamics. This work studies the dynamics of a simple microswimmer model with one or two magnetized links connected by an elastic joint, which undergoes planar undulations induced by an oscillating magnetic field. The nonlinear dynamics of the microswimmer is formulated by assuming Stokes flow and using resistive force theory to calculate the viscous drag forces. Key effects that enable the swimmer to overcome the scallop theorem and generate net propulsion are identified, including violation of front-back symmetry. Assuming small oscillation amplitude, approximate solution is derived by using perturbation expansion, and leading-order expressions for the swimmer's displacement per cycle X and average speed V are obtained. Optimal actuation frequencies that maximize X or V are found for given swimmer's parameters. An ultimate optimal choice of swimmer's parameters and actuation frequency is found, for which the average swimming speed V attains a global maximum. Finally, the theoretical predictions of optimal performance values are validated by comparison to reported experimental results of magnetic microswimmers.

Swimmers utilizing surface traveling waves: Analytical and experimental study

Shimon Haber, Eyal Setter and Izhak Bucher

Faculty of Mechanical Engineering, Technion - Israel Institute of Technology, Israel

Microscale slender swimmers are frequently encountered in nature and are now used in microrobotic applications. The swimming mechanism examined in this paper is based on small transverse axisymmetric travelingwave deformations of a cylindrical long shell. The thin-shelled device is assumed to be inextensible at the middle surface and extensible at the surface wetted by the fluid.Assuming low-Reynolds-number hydrodynamics, an analytical solution is derived for waves of small amplitudes compared with the cylinder diameter. We show that swimming velocity increases with β1 (the ratio of cylinder radius to wavelength) and that swimming velocity is linearly dependent on wave propagation velocity, increasing to leading order with the square of the ratio of wave amplitude to wavelength β2 and decreasing with the wall thickness. A fourth-order correction in β2 was also calculated and was found to have a negative effect on the swimming velocity. The results for a shell of negligible-wall thickness were compared with Taylor's solution for an inextensible two-dimensional flat membrane undergoing a waving motion and Felderhof's results [Phys. Fluids 22, 113604 (2010)] for an unbounded flow field and negligible-wall thickness. We show that Taylor's analytic solution is a particular limiting case of the present solution, assuming zero wall thickness and infinite values of β1. The present mechanism was also compared with Taylor's well known solutions of waving planar and helical circular tails. We show that the present approach yields higher velocities as β1 increases, whereas, the opposite occurs for waving tails. Indeed, in the region where β1 > 15, the present approach yields velocities nearly as fast as Taylor's helical waving tail while consuming less power and with a design that is considerably more compact. In this regime, the axisymmetric swimmer is twice as fast as Taylor's planar-tail swimmer for an additional investment of only one-third of the power. Experiments were conducted using a macroscale autonomous model immersed in highly viscous silicone fluid. We outlined how the proposed mechanism was realized to propel an elongated, yet finite, swimmer. Measured data demonstrate the effects of wave velocity and wavelength on swimming speed, showing good agreement with analytical results.

Orientation and propulsion of externally actuated chiral nanomotors.

Konstantin I. Morozov

Faculty of Chemical Engineering, Technion - Israel Institute of Technology, Israel

An analytical theory of dynamic orientation and propulsion of two different types of the chiral nanomotors – magnetizable and superparamagnetic – powered by a rotating magnetic field is developed. An overdamped dynamics of nanomotors of both types can be realized via synchronous and asynchronous regimes. At low frequency of actuating field, the nanomotors tumble synchronously in the plane of the field rotation. The transition to propulsive (wobbling) synchronous regime occurs upon growth of the field frequency with the transition frequency being different for both types of nanomotors. In the case of magnetizable nanomotors, the transition is due to transverse magnetization of helices, whereas the longitudinal (along the helical axis) magnetization postpones the transition and shifts it to higher values of the driving frequencies. If the transverse magnetization component is absent, the transition to propulsive regime is impossible. On the other hand, the transversely magnetized nanomotors avoid tumbling at all frequencies, they are always in the propulsive mode. In contrast, the propulsive ability of superparamagnetic nanomotors is not controlled only by the orientation of the magnetic easy axis, but also by the geometry of the propeller. Based on the theory we introduce a novel "steerability" parameter γ to rank polarizable nanomotors by their propulsive capacity. The theoretical predictions for orientation and propulsion speed are in excellent agreement with recent experimental results by Ghosh et al. (2012) for magnetizable nanomotors and by Nelson et al. (2013) for superparamagnetic nanohelices. Finally, we determine numerically the effective magnetic anisotropy of the polarizable helices with random distribution of magnetic particles and compare the results with predictions of a slender-body approximation.

Comparative study of actuation methods for robotic micro-swimmers

Gábor Kósa

School of Mechanical Engineering, Tel Aviv University, Israel

Microrobots have great potential for enabling medical interventional and diagnostic medical procedures. The actuation and powering are the greatest challenges in robots at such scale. Our hypothesis is that a microrobot for medical application should be from a size of a medical pill (10 mm) down to the order of 10 µm.

A plethora of swimming actuators for micro robots has been developed. They are based mostly on magnetic, piezoelectric, electroactive polymer and other actuation principles. This abundance suggests that there is no dominant solution for the propulsion of a micro robot in a fluidic environment.

We evaluate the potential of an actuation method by estimating the scaling of its performance. We model the different micro swimmers and derive the scaling of their propulsive velocity, force, power and efficiency. We also compare the artificial swimming micro robot to natural micro swimmers such as sperms and nematodes.

We found that the propulsion method of a traveling wave created in an elastic beam is the most effective judging by the aspect of down scaling. Using piezoelectric actuation principle, the amplitude of the traveling wave scales as $w \propto s$. This leads to the propulsive velocity that remains constant when the geometry of the actuator scales down with the proportion s.

Spinning Janus doublets in AC electric fields

A.M Boymelgreen,[a] G. Yossifon,[a] and T. Miloh[b]

[a] *Faculty of Mechanical Engineering, Technion, Israel*
[b] *Department of Mechanical Engineering, Tel Aviv University, Israel*

We investigate experimentally and theoretically the non-linear electrokinetic behaviour of Janus spheres comprised of one conducting (gold) and one dielectric (polystyrene) hemisphere under the influence of an AC eletric field. The intrinsic asymmetry of the Janus sphere distorts the quadrupolar induced-charge electrokinetic flow which is characteristic of uncharged homogeneous particles suspended in an infinite medium and subject to a uniform electric field [1]. The result is a finite velocity (even under ac forcing), generally termed "induced-charge electrophoresis." In fact, the particle first orients itself to its sole stable state in which its interface (the line dividing between the conducting and dielectric hemispheres) is aligned parallel to the electric field, at which point it will travel perpendicular to the field with its dielectric end facing forward [2,3].

We have shown that when two spheres are rigidly attached one to the other, they will continuously rotate, with the radius and angular velocity determined by the alignment of the interfaces between the metallic and dielectric hemispheres of each particle [4]. The data was well-fitted using a simple kinematic rigid body model, suggesting little interference between the hydrodynamic flow around each particle. To further evaluate this hypothesis, we present here 3D PIV images of the hydrodynamic flow around stationary pairs of Janus particles. Examination of this flow over a broad spectrum of frequencies reveals competing effects such as dielectrophoresis and alternating-current electroosmosis that could be partially responsible for quantitative discrepancies between the theory and experiment, specifically in terms of velocity magnitude and frequency dispersion.

References

[1] T. M. Squires, M. Z. Bazant. *J. Fluid Mech.* ***508***, 217 (2004)

[2] T. M. Squires, M. Z. Bazant. *J. Fluid Mech.* ***560***, 65 (2006)

[3] S. Gangwal, O. J. Cayre, M. Z. Bazant, O. D. Velev. *Phys. Rev. Lett.* ***100***, 058302 (2008)

[4] A.M Boymelgreen, G. Yossifon, S. Park, T. Miloh, *PRE Rapid*, ***89***, 011003 (2014)

Quantum swimmers in Fermi sea

Joseph Avron

Faculty of Physics, Technion - Israel Institute of Technology, Israel

Interference effects are important for swimming of mesoscopic systems in a quantum medium. Swimming is geometric for slow swimmers and topological in a one-dimensionion at zero temperature: the swimming distance covered in one stroke is quantized in half integer multiples of the Fermi wavelength. Based on 2006 work with B. Gutkin and D. Oaknin.

Osmotic self-propulsion of rod-shaped particles

Ehud Yariv

Faculty of Mathematics, Technion - Israel Institute of Technology, Israel

We consider self-diffusiophoresis of axisymmetric particles using a continuum description where the chemical reaction at the particle boundary is modelled by a prescribed distribution of solute absorption and the interaction of solute molecules with that boundary is represented by diffusio-osmotic slip. With a view towards modelling of needle-like particle shapes, commonly employed in experiments, the self-propulsion problem is analyzed using slender-body theory. We obtain a remarkably simple approximation for the particle velocity, which can accommodate discontinuous flux distributions commonly used for describing bimetallic particles; it agrees strikingly well with the numerical calculations of Popescu et al. [Eur. Phys. J. E Soft Matter 31, 351--367 (2010)], performed for spheroidal particles.