HARNESSING VISCOUS STREAMING IN COMPLEX ACTIVE SYSTEMS: MINIBOTS IN FLUIDS

Allocation: Strategic/480 Knh
PI: Mattia Gazzola[1]

[1]University of Illinois at Urbana–Champaign

EXECUTIVE SUMMARY

Demonstrations of artificial and biohybrid (partly synthetic, partly biological) miniaturized swimming robots have underscored their potential as diagnostic and therapeutic vehicles, as well as the lack of and need for rigorous engineering methods for design and flow control. A brief survey reveals that most prototypes operate in flow regimes where viscous streaming can be leveraged. Streaming generates rectified flows in response to body-fluid oscillations and offers powerful control options for transport, mixing, drug delivery, and assembly. Thus, although streaming is not currently being exploited, it aligns well with minibots' intended applications. One reason for this is that although streaming phenomena are well understood for simple bodies of uniform curvature, little is known in the case of complex, active geometries. Therefore, this project brings together modeling, simulations, and experiments to understand how viscous streaming relates to body morphology and aims to connect this understanding to biology and robotics to enhance the capabilities of current minibots.

RESEARCH CHALLENGE

The long-term goal of this work is to enable the rational design of miniaturized robots capable of operating in uncertain flow environments, of navigating the bloodstream, and of delivering localized treatment. The researcher is motivated by recent proof-of-concept demonstrations of artificial and living minibots in fluids, by their potential as diagnostic and therapeutic vectors, and by the lack of and need for rigorous engineering methods for design and flow control.

Toward this vision, the PI has revisited a well-known fluid dynamic effect: viscous streaming. This fluid mechanism takes place when an immersed body oscillates within specific size–frequency ratios (which happen to overlap with minibots' operating conditions), and is responsible for the emergence of characteristic rectified flows via nonlinear fluid responses (Fig. 1). These structures offer appealing flow control options for particle manipulation, transport, and mixing. Larvae and large bacteria might also exploit and control them through body shape changes for feeding and locomotion. Thus, streaming aligns well with minibots' intended applications, although it is not presently exploited.

Although viscous streaming is classically understood in the case of basic objects of uniform curvature such as plates, cylinders, and spheres, the PI hypothesized that morphological shape changes that introduce multiple curvatures can challenge this understanding and qualitatively affect the flow topology response, potentially providing ways to enhance flow control. The results from this project corroborate this hypothesis, and set the stage to revisit viscous streaming in a novel engineering context to improve the design and capability of minibots. Thus, the goal is to understand the relationship of body curvature to streaming and exploit it for biomedical applications.

METHODS & CODES

The characterization of propulsion and transport in fluids demands accurate, robust, fast, and flexible numerics for flow–structure interaction problems. The PI has been developing and implementing novel schemes for the direct numerical simulation of individual and multiple swimming bodies. His algorithms rely on remeshed vortex methods enhanced with a projection approach to capture the effects of the fluid on the body, and with a penalization technique, to capture the effects of the body on the fluid [1,2]. This methodology is coupled with a musculoskeletal solver developed to capture the compliant dynamics of musculoskeletal systems made of bones, tendons, and muscles or, in the case of biohybrid robots, made of muscles and artificial scaffolds [3].

RESULTS & IMPACT

This research has shown that oscillations can be utilized to improve transport robustly in an idealized two-dimensional master–slave setting across intermediate Reynolds numbers ($1 \leqslant Re \leqslant 100$). The analysis of flow features identifies viscous streaming as the catalyst for this improvement. In order to leverage this information, the PI designed geometries exhibiting more favorable streaming patterns, which resulted in improved slave transport. To that extent, this project demonstrated a rational design approach by modifying the classic circular cylinder via the introduction of multiple curvatures and fore–aft symmetry breaking. Moreover, the work showed that similar concepts extend to three dimensions even though favorable streaming effects are activated differently [4].

Concurrently, the PI has developed Elastica [3], a software that captures the dynamic response of complex musculoskeletal architectures via assemblies of Cosserat rods [3,5]. In particular, the PI employed Elastica to computationally design, simulate, and optimize the structure of a biohybrid walking bot [6] and a biohybrid swimmer that combines neurons and muscles [7]. In collaboration with experimentalists, these designs were fabricated and tested, confirming the predictive capacity. These results illustrate the biophysical accuracy of the PI's solvers, rendering them powerful tools for the engineering design, optimization, and synthesis of microrobots operating in fluids.

WHY BLUE WATERS

Blue Waters' sheer size and cutting-edge technology enables optimization processes that entail thousands of simulations. This allows the design of unprecedented biological architectures, bringing within reach novel high-impact applications, from soft robotics and biomedicine to precision manipulation and fabrication.

PUBLICATIONS & DATA SETS

M. Gazzola, P. Chatelain, W. van Rees, and P. Koumoutsakos, "Simulations of single and multiple swimmers with non-divergence free deforming geometries," *J. Computat. Phys.*, vol. 230, pp. 7093–7114, 2011.

M. Gazzola, B. Hejazialhosseini, and P. Koumoutsakos, "Reinforcement learning and wavelet adapted vortex methods for simulations of self-propelled swimmers," *SIAM J. Sci. Comput.*, vol. 36, pp. B622–B639, 2014.

M. Gazzola, L. Dudte, A. McCormick, and L. Mahadevan, "Forward and inverse problems in the mechanics of soft filaments," *Royal Soc. Open Sci.*, vol. 5, no. 6, 2018, doi: 10.1098/rsos.171628.

T. Parthasarathy, F. Chan, and M. Gazzola, "Streaming enhanced flow mediated transport," *J. Fluid Mech.*, accepted, 2019.

X. Zhang, F. Chan, and M. Gazzola, "Modeling and simulation of complex musculoskeletal architectures," *Nat. Commun.*, under revision, 2019.

G. J. Pagan–Diaz *et al.*, "Simulation and fabrication of stronger, larger and faster walking biohybrid machines," *Adv. Funct. Mat.*, vol. 28, no. 23, 2018, doi: 10.1002/adfm.201801145.

O. Aydin, X. Zhang, S. Nuethong, G. Pagan–Diaz, R. Bashir, M. Gazzola, and M. Saif, "Neuromuscular actuation of biohybrid motile bots," *Proc. Natl. Acad. Sci. U.S.A.*, under revision, 2019.

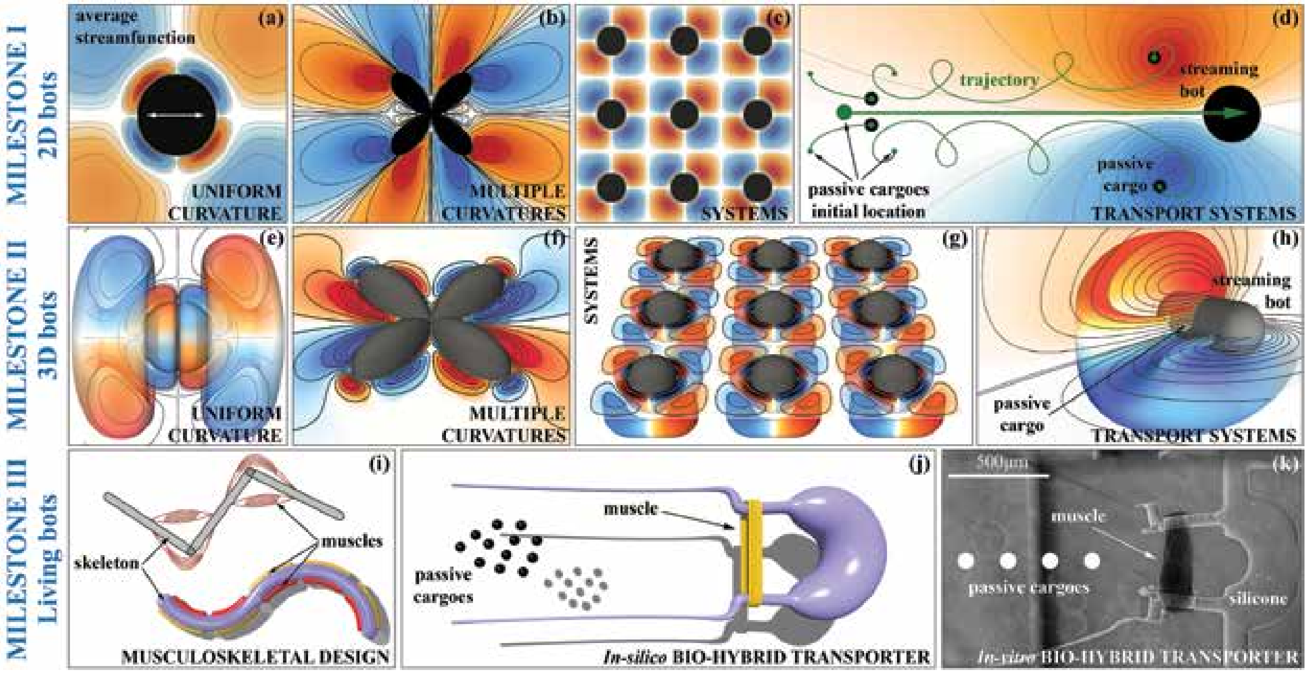

Figure 1: Goal—understand/exploit the nexus (body shape)–(viscous streaming) in 2D, 3D, and biohybrid bots for drug delivery.