Designing Life-Like Matter: From Swimming and Swarming to Shape-Shifting Vesicles

Hanumantha Rao Vutukuri

Active Soft Matter Lab, MESA+ Institute, University of Twente, The Netherlands

What if materials could move, organize, and reshape themselves like living systems? Active and living matter offers a physical route toward this goal: it is built from autonomous microscopic units that consume energy, interact locally, and collectively generate dynamic behaviour. In these systems, complex functions emerge from the interplay between energy input, geometry, interactions, fluid flows, and the surrounding medium. A major challenge for science and engineering is to recreate such life-like behaviour in synthetic materials, enabling matter to adapt, respond, and function far from equilibrium.

In this talk, I will show how simple physical ingredients, including particle shape, local interactions, fluid flows, and confinement, can produce rich collective dynamics. Our lab combines soft matter physics, colloidal chemistry, and bio-inspired design to create two complementary classes of active systems: artificial microswimmers and active lipid vesicles. Together, they provide model platforms for understanding how microscopic activity can be converted into collective organization, shape transformation, and function.

The first part of the talk will focus on artificial microswimmers, micron-sized particles that move by converting light or chemical energy into motion. I will introduce our experimental toolbox of active units with programmable motion and responsiveness to local cues, including rotators, artificial flagella-like swimmers [1], and light-controlled particles whose propulsion direction can be reversed [2]. These modular self-propelled units allow us to encode different search strategies, including Lévy walks and run-and-tumble motion. This gives us a controllable way to ask a basic question: how do many simple moving particles begin to behave as a coordinated material? I will then highlight our recent Science work on light-driven polar rods that mimic key aspects of bacterial motility [3]. These simple active rods reveal how particle shape, alignment, collisions, and hydrodynamic coupling can generate swarms, flocks, active turbulence, clusters, and jammed states. The result is a direct experimental route to designing collective motion in synthetic active matter.

The second part will move from swimming particles to soft boundaries: lipid membranes that can bend, fluctuate, and change shape. Giant unilamellar vesicles (GUVs) serve as minimal models of cell membranes, while enclosed self-propelled particles generate forces from within [4]. I will show that even forces as small as 0.1 pN can strongly deform vesicles and drive active membrane fluctuations. This provides a simple physical picture of how internal activity can remodel soft biological-like compartments. I will also discuss how membrane curvature, particle geometry, deformability, and adhesion can be used to control endocytosis-like pathways, from shallow wrapping to full internalization [5-7]. Finally, I will present our very recent work on flexible vesicles containing rods [8]. In this system, the vesicle shape guides the organization of the rods, while the rods simultaneously reshape the vesicle itself. Together, these studies point toward design principles for active soft matter, synthetic cells, and future micron-scale soft robotic systems.

References:

1. H. R. Vutukuri, et al., Rational design and dynamics of self-propelled colloidal bead chains: from rotators to flagella, Scientific Reports, 7, 16758 (2018).
2. H. R. Vutukuri, et al., Light-switchable propulsion of active particles with reversible interactions, Nature Communications, 11, 2628 (2020).
3. Y. Shelke, A. S. Nair, and H. R. Vutukuri, Shape anisotropy governs organization of active rods: Swarming, turbulence, flocking, and jamming, Science, 392, 202-206 (2026). Featured on the Cover Page
4. H. R. Vutukuri, et al., Active particles induce large shape deformations in giant lipid vesicles, Nature, 586, 52-56 (2020).
5. S. van der Ham, J. Agudo-Canalejo, and H. R. Vutukuri, Role of shape in particle-lipid membrane interactions: From surfing to full engulfment, ACS Nano (2024).

6. S. Marín-Aguilar, F. Camerin, S. van der Ham, M. Dijkstra, and H. R. Vutukuri, A colloidal viewpoint on the sausage catastrophe and the finite sphere packing problem, Nature Communications (2023).
7. S. van der Ham, A. Brown, H. Kusumaraja, and H. R. Vutukuri, From shallow to full wrapping: Geometry and deformability dictate lipid vesicle internalization, Nano Letters (2025).
8. S. van der Ham, A. F. V. Matias, M. Dijkstra, and H. R. Vutukuri, Dynamic bidirectional coupling of membrane morphology and rod organization in flexible vesicles, PNAS, 123, e2604848123 (2026).

Short Bio:

I am an Associate Professor in the Faculty of Science and Technology at the University of Twente, where I lead the Active Soft Matter Group. My group explores how simple physical principles generate life-like behaviours such as autonomous motion, dynamic self-organization, and adaptability. To address these questions, we develop biomimetic model systems, including artificial microswimmers and active lipid vesicles, to study matter far from equilibrium. By combining soft matter physics, biophysics, materials science, and real-space imaging, we aim to uncover fundamental mechanisms and translate them into reconfigurable, adaptive, bioinspired materials. Supported by prestigious grants including an ERC Consolidator Grant and an NWO-M1 grant, our research has been published in leading journals such as Science, Nature, PNAS, Nature Physics, Nature Communications, and ACS Nano.