nature nanotechnology

Perspective

https://doi.org/10.1038/s41565-025-01962-9

A roadmap for next-generation nanomotors

Received: 21 January 2025

Accepted: 15 May 2025

Published online: 01 August 2025

Check for updates

Shuqin Chen[1,2], Donglei Emma Fan[3,4], Peer Fischer[5,6,7,8], Ambarish Ghosh[9,10], Kerstin Göpfrich[11], Ramin Golestanian[12,13], Henry Hess[14], Xing Ma[15,16], Bradley J. Nelson[17], Tania Patiño Padial[18], Jinyao Tang[19], Katherine Villa[20], Wei Wang[21], Li Zhang[22], Ayusman Sen[23,24,25] ✉ & Samuel Sánchez[1,26] ✉

Since their discovery in 2004, there has been remarkable progress in research on nanomotors, from the elucidation of different propulsion mechanisms to the study of their collective behaviour, culminating in investigations into their applications in biomedicine and environmental remediation. This Perspective reviews this evolution in nanomotor research and discusses the key challenges ahead, including the need for developing advanced characterization techniques, precise motion control, materials innovation, theory and modelling, and translationally feasible in vivo biomedical applications. These challenges highlight the current limitations of synthetic nanomotors and point to exciting future opportunities to revolutionize theranostics and create 'living' hybrid systems. We introduce the concept of 'systems materials' to encompass interacting functional materials across length scales from molecular to macro. Thus, this Perspective aims to inspire future generations of researchers to advance both fundamental understanding and practical breakthroughs, thereby engineering a paradigm shift in nanomotor research.

The field of self-propelled nano- and microparticles, known collectively as nanomotors, celebrated its twentieth birthday following two decades of continuous growth. Its inception can be traced to an experimental paper from the Pennsylvania State University in 2004[1], followed closely by another publication from the University of Toronto[2]. Around the same time, two conference papers from the Swiss Federal Institute of Technology in Zurich described magnetic nanomotors[3,4]. Independently, a theoretical paper suggested the possibility of the design of nanomotors based on the asymmetric distribution of reaction products[5] (Fig. 1). The first experimental nanomotors were bimetallic rods and spherical Janus particles propelled by the catalytic conversion of hydrogen peroxide to products produced asymmetrically across the body of the nanomotors, leading to force-free phoretic transport[1,2,6]. Another class of chemical nanomotors achieved propulsion by generating gas bubbles inside microtubular jets, which were expelled preferentially from one end, enabling directional motion[7].

Other nanomotors were developed using external light[8–10], and magnetic[11–13], electric[14,15] and acoustic[16–20] fields. In addition to these experimental advances, a theoretical proposal for a nanoscale artificial swimmer that breaks time-reversal symmetry[21], followed by an experimental demonstration involving a linear chain of colloidal magnetic particles linked by DNA, which appeared in 2004–2005[22].

Over 20 years, this field has evolved from the study of single-particle motion to the study of emergent behaviour, from directional chemotactic motility[23–26] to dynamic assembly based on interactions among themselves[27–33] and with the environment[34–39]. The potential applications of these synthetic active materials are vast. They can remodel themselves and their environment, and self-organize and evolve their structures and functions to improve their performance, accomplishing tasks collectively. Practical applications, including sensing[40–43], directed cargo and drug delivery[44–50], in vivo imaging[51–56], theranostics[57,58] (Table 1) and environmental remediation[59–63] (Table 2) are being actively explored. From a fundamental standpoint, energy-harvesting nanomotors have emerged from scientific curiosities to powerful models for studying complex systems.

A full list of affiliations appears at the end of the paper ✉e-mail: asen@psu.edu; ssanchez@ibecbarcelona.eu

https://doi.org/10.1038/s41565-025-01962-9

Recent reviews have comprehensively covered the state of the art, focusing on materials[64], propulsion mechanisms[65,66], and applications in biomedicine[67], sensing[68] and the environment[69]. This Perspective aims to spark discussion on the challenges, opportunities and future directions in the field.

Today, two decades after the first examples, scientists have the opportunity to address fundamental questions in active, non-equilibrium systems, the matter-to-life transition and synthetic cells, and demonstrate realistic applications that were unimaginable 20 years ago. Scalable tools now enable smart nanomotors from almost any material and configuration, along with set-ups, and microfluidic devices that offer considerable control over the systems. In addition, artificial intelligence and computational tools are now accessible to explore and resolve questions that were previously beyond reach. Although regulatory and ethical considerations are progressing faster than ever (albeit not as swiftly as desired), this field is nearing in vivo and patient-based applications. Along with remarkable opportunities comes a myriad of challenges. Addressing these will require multi-disciplinary collaborations among physicists, chemists, engineers, biologists and medical practitioners.

Gaps and challenges

Although the field of nanomotors has made notable advances since its inception 20 years ago, there remain substantial gaps in our fundamental understanding of the behaviour of these nano- and microscale out-of-equilibrium systems both at the single-particle level and in the form of swarms. These are especially pressing issues as the size of the nanomotors approaches the scale of macromolecules. New ways to design nanomotors and control their motility and dynamic assembly are critically important. In addition, there are challenges in characterizing and tracking the motors, especially in vivo (Fig. 2).

The need for new and accurate characterization techniques

As we learn more about nanomotors and their motion in complex fluids and biological environments, improving the techniques used to monitor them becomes critical. It is necessary to increase resolution in size and accuracy for tracking, and to find ways to measure the forces at play and the means to observe chemical processes at the single-nanomotor level. This is essential to understand the underlying physical and chemical mechanisms. New measurement techniques and cross-validation by different methods will become crucial, as well as close coupling to theoretical modelling. Magnetic nanomotors provide a distinct advantage as the magnitude and direction of the forces exerted by the nanomotors can be controlled externally with high precision[70]. This enables quantitative estimates of the local environment[71] and improves targeting.

Because of their anticipated important future impact on theranostics, it is necessary to be able to track nanomotors in vivo and understand their dynamic interactions with the biological environment. Cells, tissues and organoids show spatiotemporally varying mechanical properties and have optical characteristics that could present challenges in real-time characterization of propulsion[72] and the accurate processing of information obtained from nanomotors. Despite progress in microscopy, in vivo tracking remains challenging, as real-time imaging and long-term tracking tools are still lacking.

One can also imagine applications where direct image-guided navigation of nanomotors may not be necessary. For example, the properties of the surrounding medium, possibly defined through topography[73], charge[74] and surface chemistry[75], can ensure fast and accurate movement by the active motors, such as reaching the region of interest without external navigation control[76].

Controlling motion: from single particles to swarms

Current nanomotor technology is largely limited by accuracy, controllability, self-adaptiveness, and the ability to generate sufficient

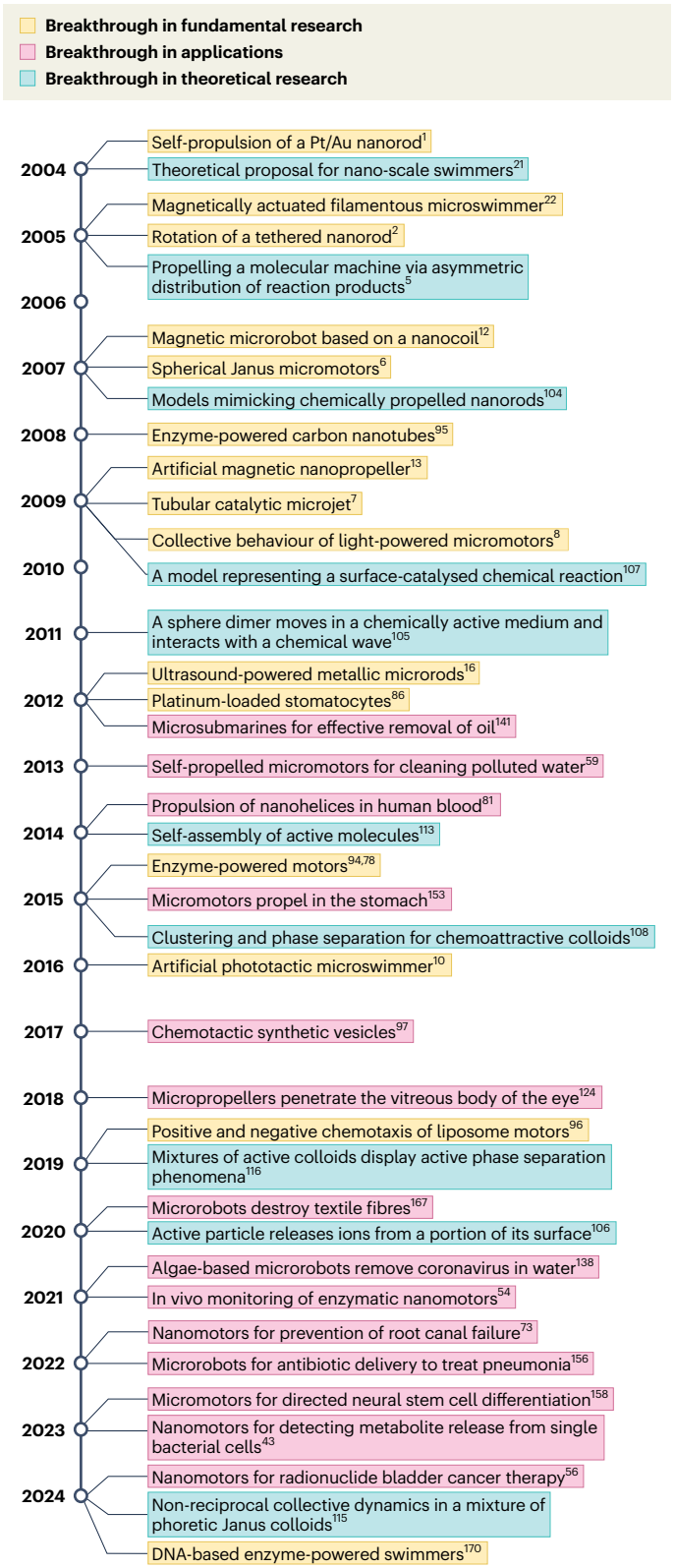

Fig. 1 | Timeline of key breakthroughs in nanomotor development. The inception of self-propelled nanomotors dates back to 2004. Over the past two decades, the field has witnessed substantial breakthroughs, with the development of nanomotors powered by chemical, magnetic, acoustic, light, and electric stimuli. The field has made substantial advances in both experiments and theory, progressing from the study of individual nanomotor self-propulsion to the collective behaviour of multiple communicating nanomotors. These advances are contributing to emerging applications in biomedicine and environmental remediation.

https://doi.org/10.1038/s41565-025-01962-9

Table 1 | Breakthrough in vivo applications

Applications	Size	Material composition
Enhanced retention in the stomach	20 μm length	Poly(3,4-ethylenedioxythiophene) (PEDOT)/Zn microtubes[153]
Position and propel in gastrointestinal tract	15 μm length	Mg/PEDOT/Au microtubes[154]
Treatment of stomach infection	~20 μm	Mg/TiO_2/poly(lactic-co-glycolic acid) (PLGA)/chitosan micromotors[155]
In vivo imaging-guided therapy	~200 μm length	Biohybrid microalgae/Fe_3O_4 helical microswimmers[58]
Penetration of the vitreous body of the eye	2 μm length	SiO_2/Ni microhelices/perfluorocarbon micropropellers[124]
Targeted navigation in intestines	20 μm	Mg/Au/parylene micromotors[55]
Skin penetration and synergistic antifungal therapy	~80 nm	Poly(divinylbenzene)/Pt nanomotors[128]
In vivo monitoring within the bladder	450 nm	Mesoporous silica nanoparticle (MSNP)-urease/polyethylene glycol (PEG)-Au nanomotors[54]
In vivo antibiotic delivery to treat acute bacterial pneumonia	~10 μm	Microalgae/neutrophil membrane/ PLGA biohybrid microrobots[156]
Targeted delivery in bile duct	~1 mm diameter	Hydrogel/NdFeB microrobots[157]
Directed neural stem cells differentiation	~6 μm length	Ni–Zn micromotors[158]
Imaging and bladder cancer treatment	450 nm	MSNP-urease/PEG-Au nanomotors[56]
Urease-nanomotors for immunotherapy	600 nm	Urease/chitosan/heparin nanomotors[159]
Treatment of degenerative knee osteoarthritis	~3 μm	Vesical@MoS_2-ATPase micromotors[160]

Table 2 | Breakthrough in environmental remediation

Applications	Size	Material Composition
Detection of trace silver	~2 μm length	Au–Pt nanowires[161]
Bacterial isolation	~8 μm length	(Au/Ni/ polyaniline /Pt) microtubulars[162]
Oil removal	~8 μm	PEDOT/Pt/Ni/Au micromotors[141]
Degrading organic pollutants	500 μm length	Fe/Pt microtubes[59]
Photocatalytic degradation of biological and chemical warfare agents	~30 μm	TiO_2/Au/Mg microspheres[163]
Biofilm elimination	500 nm	Ferromagnetic nanoparticles[164]
Toxic heavy metal removal	~5 μm diameter	Graphene oxide/Pt/Ni layer/Ni/Pt microbots[165]
Bacterial endotoxin detection	~20 μm	Fe_3O_4/Pt/graphene quantum dot micromotors[166]
Microorganisms capture	~4–8 μm	$BiVO_4$ micromotors[62]
Destroy textile fibres	~7 μm	Bi_2WO_6 microrobots[167]
Positive chemotaxis towards CO_2	2.5 μm	ZnO/SiO_2 micromotors[168]
Trapping and detecting nanoplastics	~10 μm	MXene-derived γ-Fe_2O_3/Pt/TiO_2 microrobots[169]
Ammonia generation	~15 μm length	MnO_2/laccase micromotors[142]

forces and torques. In particular, generating the desired forces and torques for operation in complex environments using untethered small robots is challenging, especially when these forces should be higher than what individual nanomotors can typically offer. Currently, most nanomotors exert forces in the range of nanonewtons to piconewtons[77], with enzymatic nanomotors operating at the piconewton level[78,79], similar to biological protein motors. This greatly restricts their ability to traverse biological barriers and perform effective mechanical operations. Addressing this challenge demands developing innovative concepts, actuation mechanisms, new materials and improved structural design. If external fields are employed, auxiliary instrumentation must be developed to ensure that it is compatible with existing medical technologies, and safe and user-friendly for clinical applications.

Integrated nanorobotic systems require better controllability over several degrees of freedom. This calls for improved material combinations that enable multiple addressable propulsion mechanisms, including chemical, light, electric, magnetic and acoustic forces.

Another challenge is coordinating multiple nanoscale motors for macroscale actuation and function, as in biology. The amplification may arise via the environment or coupling of chemical processes to fluidic effects in suitable geometries[80]. However, it is challenging to endow swarms composed of simple building blocks with complex collective behaviours. Coordinating multiple different motor–motor interactions within a swarm, and regulating the impact of the external environment on the swarm, can be difficult. Yet, it is an exciting phenomenon to be studied. These difficulties pose a challenge to the design of nanomotor-based swarms that exhibit hierarchical functions and even embodied intelligence, for example, swarms capable of perceiving diverse environmental stimuli in an unstructured environment and making corresponding adaptations.

Material needs for nanomotors: from inorganic to biohybrid

Although nanomotor propulsion and navigation methods have been substantially advanced with two decades of research, better adaptability and biocompatibility are still required for the application of nanomotors. Particularly in the biomedical field, long-term performance is crucial in a complex physiological environment with its associated high ionic strength, high viscosity and potential plasma protein biofouling. Surface coating has been extensively used to encode multiple functions and regulate propulsion efficiency for nanomotors. Optimizing the material composition to balance biomedical needs[81,82], while realizing multiple functions and keeping the composition simple for scalability, remains an unfinished task.

Some of the best-controlled nanomotors are magnetic[13,83]. A challenge is to find magnetic materials with strong magnetic moments and high remanence and coercivity that are also biocompatible and stable against physical agglomeration at high densities. Progress in this direction has been made with the biocompatible hard magnetic FePt system[84], and with ZnFe coating[82], which protects against physical agglomeration while allowing magnetic hyperthermia. Including Mg and Zn in the scaffold of the nanomotors allows the degradation to be tuned[85]. Ideally, one should employ hard magnetic materials that are also biodegradable. Combining materials in hybrid nanomotors will require testing to determine safe operating conditions. As such, systematic screening and testing protocols will be helpful for the field. For example, molecules, particles and cells exhibit motion under direct-current voltage or high-frequency signals. As a result, electric manipulation holds notable potential for creating reconfigurable motors and diverse swarms.

Developing new materials and creating hybrid structures with controlled chemistry[86], dimensions and assembly could enable distinct mechanical behaviours in response to a given electric frequency, allowing for precise control within a swarm[87–89].

https://doi.org/10.1038/s41565-025-01962-9

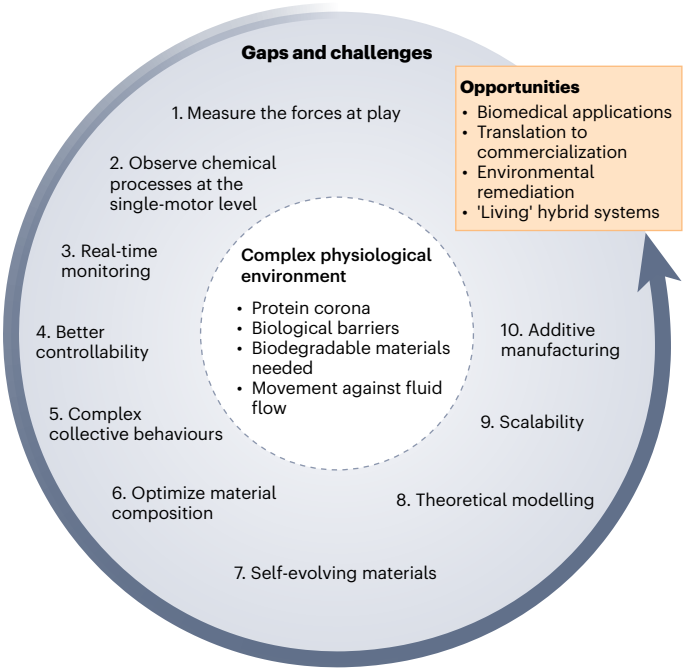

Fig. 2 | Gaps and challenges in nanomotor development provide opportunities for future innovation. In complex physiological environments, challenges posed by the protein corona, the presence of biological barriers and biofluid flow present key obstacles for in vivo applications of nanomotors. Other gaps and challenges remain across technology, materials and theoretical modelling. Addressing these issues not only advances fundamental research but also opens exciting opportunities in biomedical applications, environmental remediation and the development of augmented living systems.

Externally imposed light represents useful energy input for powering nanomotors, as the light source is easily moved and enables tight spatiotemporal control over nanomotor motility[90]. Ideally, these light-driven motors should exhibit strong light absorption, high energy conversion efficiency and robust stability under operational conditions. While materials, such as inorganic semiconductors, meet some of these criteria, an ideal light-driven system that satisfies all these features is still lacking. Hence, it is essential to explore materials with diverse optical properties and to investigate zero- to three-dimensional structures[91]. For instance, small-molecule organic semiconductors that delocalize charges through their backbone, or transition metal complexes with long-lived excitation states, rich redox properties and intrinsic fluorescence[92], show promise but remain largely unexplored.

In addition, integrating these materials with those that enable energy storage and conversion, such as photochromic materials and upconversion nanoparticles[93], is crucial. This integration can yield photoactive micromotors capable of navigating non-transparent media, harvesting biocompatible wavelengths with high penetration depth and performing environmental readouts, such as temperature measurements. A major challenge is to engineer these multicomponent micromotors with asymmetrical structures and effectively coordinate the multistep charge and energy transfer among materials to achieve precise motion control upon photoactivation.

Enzyme-powered nanomotors have been explored for their potential use in generating in situ chemicals for disease treatment, embodying the concept of a circular economy at the micro- and nanoscale. Their versatility, use of bio-available fuels, ease of fabrication and biocompatibility[94,95] make them promising for biomedical applications. Because of the ability of enzymes to chemotax in response to substrate gradients, these motors can be moved directionally using such gradients[96–98]. In addition, the use of enzyme cascades potentially allows populations of particles incorporating enzymes that are part of a cascade to form dynamic assemblies[99]. However, the factors that govern chemotaxis, such as reaction kinetics, kinetic asymmetry, variations in the diffusion of bound and unbound enzymes, the effect of inhibitors and promoters, and phoretic and hydrodynamic effects, are poorly understood. Moreover, only a handful of enzymes have been employed in the studies so far[100].

Moving further, bottom-up synthetic biology has developed synthetic vesicles with complex machinery for diverse tasks, including active motion, based on natural or synthetic molecular hardware (for example, DNA and RNA origami[101,102]). These innovations offer new possibilities for the nanomotors field to bridge various scientific disciplines.

A major challenge in synthetic biology is to design 'self-evolving' systems and materials. In biology, the growth and evolution of materials involves constant turnover of building blocks, while they interact with the environment. Thus, adaptation (changes in composition and function) takes place during the lifetime of the material itself. This contrasts with synthetic materials that are typically fabricated according to predesigned parameters and then assembled. Addressing this challenge and creating synthetic systems with life-like behaviours would be game-changing, enabling materials to possess features such as memory, adaptation, self-replication and continuous evolution in response to their environment.

Theory and modelling

Modelling collective nanomotor dynamics remains challenging owing to their nonlinear, stochastic and time-delayed responses to multiple stimuli[70]. Thus, advanced algorithms capable of delivering robust and adaptive control are worthy of investigation[103]. The possibility of making local measurements using nanomotors at submicrometre resolution can provide important information that is not yet available.

A central theoretical goal is to predict large-scale swarm behaviour from the properties of individual active units. A systematic coarse-graining approach can bridge scales, but current models still lack essential ingredients such as propulsion mechanisms[104–106], stochastic fluctuations[107,108], hydrodynamic interactions and boundary effects[109,110]. These frameworks enable analysis of large-scale phase behaviour and scaling via renormalization group techniques developed for phase transitions and critical phenomena. Notably, motility and inter-motor communication in swarming stem from shared chemical gradients, a key consideration for realistic modelling.

One of the natural consequences of chemo-mechanical transduction is the emergence of non-reciprocal interactions in active matter[111–113], which prevents steady-state behaviour and exhibiting simplified equilibrium-like behaviour. The origin of non-reciprocal interactions has been proposed for nanoscale enzyme systems[114]. Importantly, non-reciprocal active matter can spontaneously break symmetry, leading to a plethora of complex collective effects[115,116]. The consequences of these theoretical predictions remain to be experimentally tested.

Theoretical frameworks can be developed through three main approaches: symmetry-based top-down, agent-based bottom-up and microscopic coarse-graining[117]. A multi-scale model that systematically incorporates key ingredients across scales is needed to define universality classes. This bottom-up understanding of control parameters will enable the design of swarm behaviour without hard-wiring each system layer.

In vivo applications of self-propelled active particles

Nanomotors hold great promise as a new paradigm in drug delivery[118]. The active delivery of drugs to a specific disease site would (1) greatly diminish the therapeutic dosage and (2) reduce collateral cytotoxicity. However, there are several challenges to achieving this goal. In many in vivo applications, nanomotors must be powerful enough to move against fluid flow, such as in circulatory systems[119,120]. This remains to

be demonstrated. However, active nanomotors exhibiting rheotaxis near walls is a useful development[121,122]. One alternative is to deploy the nanomotors locally, in confined spaces, where diffusion is limited and traditional drugs cannot easily reach the target. Examples include the bladder[56,123], eyes[124], joints[38,125], lungs[126], skin[127,128] and other locations. In general, it is important to find ways that nanomotors can either locomote themselves autonomously to the region of interest or to develop ways to navigate nanomotors inside the body[129,130].

Another challenge is the generally poor ability of active articles to reach the interior of cells, although active internalization and subsequent manipulation of magnetic and acoustic nanomotors in living cells have been demonstrated[17,131]. Particles must traverse epithelial tissue and extracellular matrix to reach and penetrate cells. It is not clear that the current nanomotors are powerful enough to cross these biological barriers that impede passive nanoparticles. However, substantial progress has been made with magnetically, acoustically and chemically driven micro- and nanomotors to move through relatively dense biological environments[35,132]. With further engineering of the materials and geometry, coupled with more sophisticated instrumentation, we envision that the 'fantastic voyage' through dense organs may soon be realized.

Finally, the delivery of optimal drug dosage would require swarms of active particles. Guiding these swarms through the body presents unique difficulties, especially when navigating the tight spaces of the tissue microenvironment, managing residual motors and mitigating the potential risk of increased cytotoxicity. These challenges require a deeper understanding and better control of swarming behaviours and the investigation of novel active degradable materials.

Opportunities

Many of the challenges discussed above also provide opportunities for future innovation. Free of biological constraints, it is now possible to probe the limits of self-organization in synthetic active systems operating far from equilibrium. Furthermore, developing micro- and nanorobotics as active tools with unparalleled precision, control, sensing, delivery and operation capabilities will unlock opportunities in both basic biological research and practical biomedical applications. These tiny machines have the potential to actively control cell–cell communication, single-cell immunology, physiology and subcellular sensing, delivery, and stimulation. They may reveal blood–brain barrier permeability at nanoscale resolution, vital for brain therapy. Advancements are expected to enable intelligent, self-powered gene delivery and editing, achieving targeted autonomous transfection with substantially higher efficacy than current techniques.

Active functional swarms

Self-assembly and organization have been topics of considerable interest in the scientific community owing to their potential to create complex, functional materials. While previous efforts have primarily focused on equilibrium systems characterized by static and predetermined structures, biological systems are known for their dynamic and diverse self-organized structures constructed from the same building blocks. As a synthetic out-of-equilibrium system, nanomotors can mimic natural self-organizing structures. Two avenues for achieving this goal are the utilization of nanomotor dissipative interactions and exploring non-reciprocal interactions. The former strategy involves replacing static interactions, such as van der Waals and Coulomb interactions, with dissipative interactions, such as hydrodynamics and chemical gradients, which can be modulated with energy input. This allows phase transitions in nanomotor assemblies, resulting in responsive materials. The other strategy involves leveraging the non-reciprocal nature of nanomotor interactions, which mimic living systems. Non-reciprocal active systems have been theoretically shown to have the capacity to form a variety of self-organized structures starting with the same building blocks, participating in a choreographed sequential assembly and disassembly of desired structures[133].

Nanomotors that respond to environmental signals and store chemical information could enable advanced tasks such as targeted cargo delivery or environmental sensing. In the complete absence of any information processing capability, a nanomotor can still be used to agitate a solution and accelerate mixing[134]. Making local measurements using nanomotors at submicrometre resolution can provide important biophysical information that is not yet available. The possibilities of engineering highly advanced systems are exemplified by the ability of white blood cells to actively pursue harmful bacteria and neutralize them. Current nanomotors can successfully alter their direction of motion in response to chemical gradients and specific attachments can selectively halt their motion[135]. Endowing the nanomotors with internal mechanisms to acquire, store and process information encoded in the concentrations of chemical molecules would greatly enhance their capabilities. Biochemical systems developed to design synthetic cells may enable transformational advances in this respect[136,137]. Macroscale systems often allow a clear delineation between the flows of energy and information, whereas in nanoscale systems, it can be a matter of individual perspective whether the information has been transmitted or processed, or a physical or chemical change has occurred. It would be desirable to switch from one perspective to the other seamlessly. This is particularly interesting when considering swarms of nanomotors interacting with each other and the environment. To what extent can a swarm of nanomotors sense inputs and process them into complex responses by leveraging the nonlinearities of the nanomotor interactions and the continuous flow of energy? The most 'futuristic' scenario involves active systems that can autonomously carry out operations such as sensing, reporting and delivery, with different populations of interacting nanomotors performing different tasks synergistically.

It should be possible to apply machine learning algorithms to swarm control. Benefiting from the strong abilities of machine learning models, impressive progress has been achieved in the design, actuation, tracking and navigation of swarms. However, the working scenarios are still limited to ex vivo conditions. It is now essential to exploit the superiority of machine learning algorithms and realize robust and adaptive control of swarms to undertake more practical biomedical tasks in dynamic fluctuating environments.

Biomedical applications

As discussed in the previous section, using nanomotors in imaging and drug delivery is an area of great promise. For this to become a reality, several roadblocks must be overcome, for example, biomedical translation requires biocompatibility, active motion in complex fluids and scalable manufacturing.

Notably, many proof-of-concept applications currently demonstrated with nanomotors suffer from the lack of clear, quantifiable comparison with existing technologies regarding the perceived improvement in patient care, which limits their subsequent translation towards commercialization. However, several nanomotor start-ups, including Nanobots Therapeutics, Bionaut Labs and Theranautilus, have secured funding and are progressing towards clinical trials. The quantifiable advantages that nanomotors could bring in biomedical applications include enhanced diffusivity and efficacy, reduced side effects, on-demand operation and thus the speed of treatment, and the ability to move in spaces that are inaccessible with existing medical techniques. Moreover, they can enhance penetration through biological barriers in addition to standard advantages claimed by passive nanobiotechnology tools.

Environmental remediation

The potential of nanomotors in environmental remediation, particularly for water purification and pollutant removal, has been extensively studied[138–141]. Recently, converting pollutants into beneficial

https://doi.org/10.1038/s41565-025-01962-9

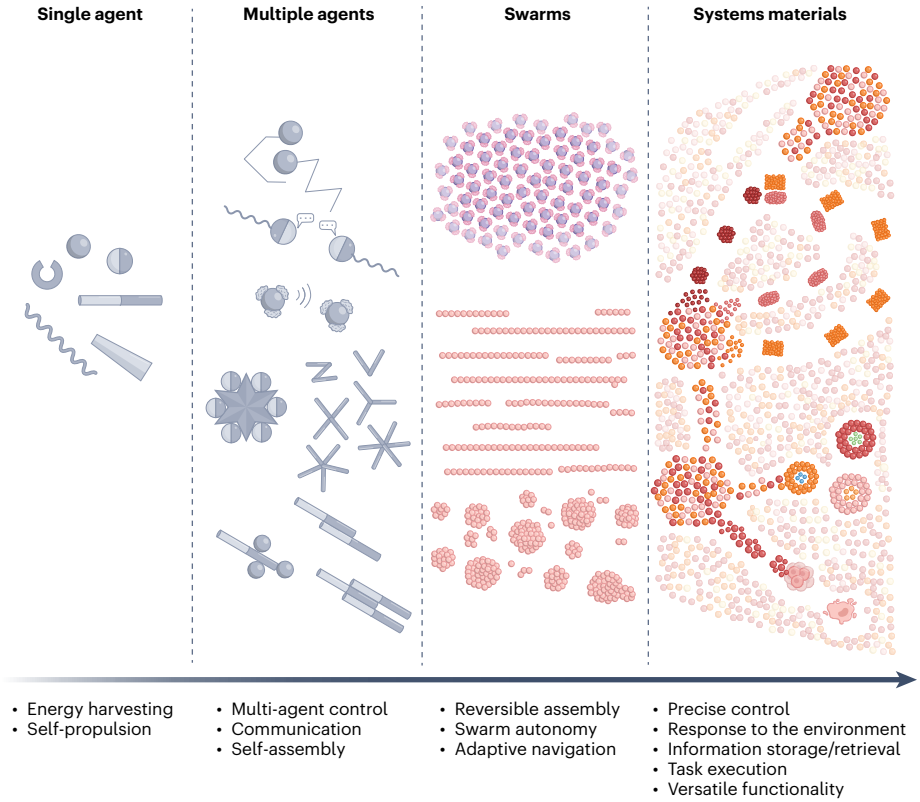

Fig. 3 | The evolution of nanomotors over 20 years and beyond. Early research focused on achieving controlled motion at the single-particle level, powered by energy harvesting from various external sources or in situ chemical reactions. As studies progressed, particle–particle interactions inspired developments in multi-agent control and the emergence of nanomotor assemblies. More recently, swarming behaviours have demonstrated higher levels of autonomy and navigation, mimicking collective behaviours found in nature. Looking ahead, future nanomotors are expected to possess precise control, environmental responsiveness, information storage and retrieval, task execution, and multifunctional capabilities.

compounds has emerged as a promising strategy for sustainability[142,143]. Despite abundant research in this area, the transition of nanomotors from proof-of-concept experiments to practical, real-world applications remains a notable challenge. Efforts should focus on scalability and cost reduction to make substantial advancements, as many reported nanomotors rely on complex fabrication methods and expensive materials. In addition, it is crucial to demonstrate the reusability of these nanomotors over multiple cycles and examine their long-term stability under constant operation[144,145]—likewise, the potential environmental toxicity of the motors themselves needs to be considered.

Integrating additive manufacturing with driven self-organization

When integrated with additive manufacturing, the remarkable versatility of nanomotors embedded within a frame structure, such as gels, combined with their sensitivity to chemical and biochemical signals, light, magnetic and electric stimuli, and so on, could endow these static structures with life-like senses and features[146,147]. These advanced constructs not only will move but also could release electrical and chemical signals, mimicking the sensory and actuation capabilities of living systems. For example, additive manufacturing can facilitate self-organization by providing geometric constraints that directly drive structural order in two-photon laser printing[148], or in conjunction with external fields. The use of ultrasound can, for instance, be used for the assembly of cells and to drive the organization of living tissues[149]. These structures could perceive their environment, respond dynamically to stimuli and interact with their surroundings in ways previously confined to science fiction.

Matter to life

Directed evolution of nanomotors could optimize function and reveal insights into life-like behaviour in (semi-)synthetic systems. Unlike nature, we can apply chosen selection pressures and rationally engineered starting points, broadening the evolutionary landscape. Thus, by subjecting nanomotor populations to selective performance criteria, optimizing their locomotion, sensing and interaction abilities may be possible.

Furthermore, an evolutionary approach to nanomotor design may shed light on the origins of motility, inform fundamental questions on the origins of life, and connect the nanomotors field to bottom-up synthetic biology as an adjacent field that recently started to recognize the power of evolutionary approaches[150]. Integrating evolvability in future nanomotor designs will pose an exciting challenge. One could imagine genetically encoded locomotion, such that rounds of mutagenesis and selection of the best swimmer can be performed.

Finally, synthetic active systems are truly biomimetic when functionally indistinguishable from their biological counterparts. A particularly intriguing opportunity is to engineer 'living' hybrid systems, in which communication and interaction between living and synthetic active matter lead to a complex organization similar to but extending beyond morphogenesis. Synthetic active matter may communicate with living cells and secrete attractants or repellants, leading to long-range cell organization and response. In addition, they may mediate cellular communication between different types of living cell, which is not possible in vivo. Thus, synthetic active matter could initiate complex multicellular interactions across multiple length scales, leading to functions and dynamics that are not observed physiologically.

Outlook

Future nanomotors should integrate energy harvesting, communication and decision-making to enable autonomous collective behaviours across scales.

The goal is to establish a new design paradigm for active functional materials by focusing on: (1) precise molecular-level control of functional building blocks; (2) motility powered by locally harvested energy; (3) rapid, reversible non-equilibrium self-assembly; (4) communication and intelligence akin to microorganisms; and (5) task execution in response to environmental and inter-motor signals[151].

A major challenge is designing 'self-evolving' systems that mimic biological evolution. Unlike static, prefabricated synthetic materials, biological materials grow through continuous turnover and interaction with their environment, enabling functional and compositional adaptation over time.

Similar to 'systems biology', which involves interactions across various length scales from cells to tissues to entire organisms, the concept of 'systems materials' can be applied to interacting materials, ranging from the molecular scale to the macroscale (Fig. 3). Understanding these behaviours requires a systems approach that integrates component properties, energy inputs and environmental context. Key questions include: (1) how do diverse nanomotor populations interact[152], and (2) how is information stored, transmitted and used for collective behaviour?

Chemical gradients can be one source of information. In catalytic cascades, one population of nanomotors generates a chemical gradient to which another nanomotor population can respond, resulting in non-reciprocal 'predator–prey' interactions between the two populations that can lead to synchronized motion and spatiotemporal assemblies[114]. A key goal is to design nanomotors that autonomously respond to chemical, light, electric or magnetic cues and change their functional behaviour accordingly.

Artificial intelligence strategies are advancing nanorobot actuation, navigation, tracking and cargo delivery. By enhancing perception and decision-making, machine learning enables nanomotors to function autonomously in complex, dynamic environments.

References

1. Paxton, W. F. et al. Catalytic nanomotors: autonomous movement of striped nanorods. *J. Am. Chem. Soc.* **126**, 13424–13431 (2004).
   A landmark study that introduced chemically powered nanomotors, launching the field of synthetic nanomotor research.
2. Fournier-Bidoz, S., Arsenault, A. C., Manners, I. & Ozin, G. A. Synthetic self-propelled nanorotors. *Chem. Commun.* **41**, 441–443 (2005).
3. Yesin, K. B., Vollmers, K. & Nelson, B. J. Analysis and design of wireless magnetically guided microrobots in body fluids. *Proc. IEEE Int. Conf. Robot. Autom.* **2**, 1333–1338 (2004).
4. Yesin, K. B., Vollmers, K. & Nelson, B. J. in *Experimental Robotics IX. Springer Tracts in Advanced Robotics* Vol. 21 (eds Ang, M. H. & Khatib, O.) 321–330 (Springer, 2006).
5. Golestanian, R., Liverpool, T. B. & Ajdari, A. Propulsion of a molecular machine by asymmetric distribution of reaction products. *Phys. Rev. Lett.* **94**, 220801 (2005).
   This research article provides the foundational theoretical framework for self-diffusiophoresis as a propulsion mechanism for nanomotors.
6. Howse, J. R. et al. Self-motile colloidal particles: from directed propulsion to random walk. *Phys. Rev. Lett.* **99**, 048102 (2007).
7. Solovev, A. A., Mei, Y., Ureña, E. B., Huang, G. & Schmidt, O. G. Catalytic microtubular jet engines self-propelled by accumulated gas bubbles. *Small* **5**, 1688–1692 (2009).
8. Ibele, M., Mallouk, T. E. & Sen, A. Schooling behavior of light-powered autonomous micromotors in water. *Angew. Chem. Int. Ed.* **121**, 3358–3362 (2009).
9. Palacci, J., Sacanna, S., Steinberg, A. P., Pine, D. J. & Chaikin, P. M. Living crystals of light-activated colloidal surfers. *Science* **339**, 933–936 (2013).
   An innovative research article highlighting light-powered active particles that form dynamic biomimetic self-assembled structures.
10. Dai, B. et al. Programmable artificial phototactic microswimmer. *Nat. Nanotechnol.* **11**, 1087–1092 (2016).
    This work demonstrated phototactic behaviour in a group of synthetic microswimmers, mimicking the collective phototactic behaviour of green algae.
11. Yesin, K. B., Vollmers, K. & Nelson, B. J. Modeling and control of untethered biomicrorobots in a fluidic environment using electromagnetic fields. *Int. J. Robot. Res.* **25**, 527–536 (2006).
12. Bell, D. J., Leutenegger, S., Hammar, K. M., Dong, L. X. & Nelson, B. J. Flagella-like propulsion for microrobots using a nanocoil and a rotating electromagnetic field. *Proc. IEEE Int. Conf. Robot. Autom.* **24**, 1128–1133 (2007).
13. Ghosh, A. & Fischer, P. Controlled propulsion of artificial magnetic nanostructured propellers. *Nano Lett.* **9**, 2243–2245 (2009).
    A groundbreaking research article that demonstrated precise propulsion and control of magnetic nanomotors in fluidic environments.
14. Fan, D. et al. Subcellular-resolution delivery of a cytokine through precisely manipulated nanowires. *Nat. Nanotechnol.* **5**, 545–551 (2010).
15. Kim, K., Xu, X., Guo, J. & Fan, D. L. Ultrahigh-speed rotating nanoelectromechanical system devices assembled from nanoscale building blocks. *Nat. Commun.* **5**, 3632 (2014).
16. Wang, W., Castro, L. A., Hoyos, M. & Mallouk, T. E. Autonomous motion of metallic microrods propelled by ultrasound. *ACS Nano* **6**, 6122–6132 (2012).
17. Wang, W. et al. Acoustic propulsion of nanorod motors inside living cells. *Angew. Chem. Int. Ed.* **53**, 3201–3204 (2014).
    The demonstration of acoustic propulsion of nanorods inside living cells.
18. Ren, L. et al. 3D steerable, acoustically powered microswimmers for single-particle manipulation. *Sci. Adv.* **5**, eaax3084 (2019).
19. Xu, T. et al. Reversible swarming and separation of self-propelled chemically powered nanomotors under acoustic fields. *J. Am. Chem. Soc.* **137**, 2163–2166 (2015).
20. Feng, J., Yuan, J. & Cho, S. K. Micropropulsion by an acoustic bubble for navigating microfluidic spaces. *Lab Chip* **15**, 1554–1562 (2015).
21. Najafi, A. & Golestanian, R. Simple swimmer at low Reynolds number: three linked spheres. *Phys. Rev. E* **69**, 062901–062904 (2004).
22. Dreyfus, R. et al. Microscopic artificial swimmers. *Nature* **437**, 862–865 (2005).
23. Hong, Y., Blackman, N. M. K., Kopp, N. D., Sen, A. & Velegol, D. Chemotaxis of nonbiological colloidal rods. *Phys. Rev. Lett.* **99**, 178103–178106 (2007).
24. Dey, K. K. et al. Chemotactic separation of enzymes. *ACS Nano* **8**, 11941–11949 (2014).
25. Baraban, L., Harazim, S. M., Sanchez, S. & Schmidt, O. G. Chemotactic behavior of catalytic motors in microfluidic channels. *Angew. Chem. Int. Ed.* **52**, 5552–5556 (2013).
26. Peng, F., Tu, Y., Van Hest, J. C. M. & Wilson, D. A. Self-guided supramolecular cargo-loaded nanomotors with chemotactic behavior towards cells. *Angew. Chem. Int. Ed.* **54**, 11662–11665 (2015).
27. Kagan, D., Balasubramanian, S. & Wang, J. Chemically triggered swarming of gold microparticles. *Angew. Chem. Int. Ed.* **123**, 523–526 (2011).
28. Wang, W., Duan, W., Sen, A. & Mallouk, T. E. Catalytically powered dynamic assembly of rod-shaped nanomotors and passive tracer particles. *Proc. Natl Acad. Sci. USA* **110**, 17744–17749 (2013).

29. Solovev, A. A., Sanchez, S. & Schmidt, O. G. Collective behaviour of self-propelled catalytic micromotors. *Nanoscale* **5**, 1284–1293 (2013).
30. Yu, J. et al. Active generation and magnetic actuation of microrobotic swarms in bio-fluids. *Nat. Commun.* **10**, 5631 (2019).
31. Xu, D. et al. Enzyme-powered liquid metal nanobots endowed with multiple biomedical functions. *ACS Nano* **15**, 11543–11554 (2021).
32. Altemose, A. et al. Chemically controlled spatiotemporal oscillations of colloidal assemblies. *Angew. Chem. Int. Ed.* **56**, 7817–7821 (2017).
33. Singh, D. P., Choudhury, U., Fischer, P. & Mark, A. G. Non-equilibrium assembly of light-activated colloidal mixtures. *Adv. Mater.* **29**, 1701328 (2017).
34. Walker, D., Käsdorf, B. T., Jeong, H. H., Lieleg, O. & Fischer, P. Enzymatically active biomimetic micropropellers for the penetration of mucin gels. *Sci. Adv.* **1**, e1500501 (2015).
35. Ramos-Docampo, M. A. et al. Microswimmers with heat delivery capacity for 3D cell spheroid penetration. *ACS Nano* **13**, 12192–12205 (2019).
36. Gardi, G., Ceron, S., Wang, W., Petersen, K. & Sitti, M. Microrobot collectives with reconfigurable morphologies, behaviors, and functions. *Nat. Commun.* **13**, 2239 (2022).
37. Chen, S. et al. Collective buoyancy-driven dynamics in swarming enzymatic nanomotors. *Nat. Commun.* **15**, 9315 (2024).
38. Ruiz-González, N. et al. Swarms of enzyme-powered nanomotors enhance the diffusion of macromolecules in viscous media. *Small* **20**, 2309387–2309403 (2024).
39. Sun, M. et al. Individual and collective manipulation of multifunctional bimodal droplets in three dimensions. *Sci. Adv.* **10**, eadp1439 (2024).
40. Patino, T. et al. Self-sensing enzyme-powered micromotors equipped with pH-responsive DNA nanoswitches. *Nano Lett.* **19**, 3440–3447 (2019).
41. Liu, X. et al. Urease-powered micromotors with spatially selective distribution of enzymes for capturing and sensing exosomes. *ACS Nano* **17**, 24343–24354 (2023).
42. Yuan, K., López, M. Á., Jurado-Sánchez, B. & Escarpa, A. Janus micromotors coated with 2D nanomaterials as dynamic interfaces for (bio)-sensing. *ACS Appl. Mater. Interfaces* **12**, 46588–46597 (2020).
43. Li, H. et al. Precise electrokinetic position and three-dimensional orientation control of a nanowire bioprobe in solution. *Nat. Nanotechnol.* **18**, 1213–1221 (2023).
44. Esteban-Fernández De Ávila, B. et al. Acoustically propelled nanomotors for intracellular siRNA delivery. *ACS Nano* **10**, 4997–5005 (2016).
45. Tu, Y. et al. Biodegradable hybrid stomatocyte nanomotors for drug delivery. *ACS Nano* **11**, 1957–1963 (2017).
46. Xu, H., Medina-Sánchez, M., Maitz, M. F., Werner, C. & Schmidt, O. G. Sperm micromotors for cargo delivery through flowing blood. *ACS Nano* **14**, 2982–2993 (2020).
47. Hortelão, A. C., Patiño, T., Perez-Jiménez, A., Blanco, À. & Sánchez, S. Enzyme-powered nanobots enhance anticancer drug delivery. *Adv. Funct. Mater.* **28**, 1705086 (2018).
48. Ma, X., Hahn, K. & Sanchez, S. Catalytic mesoporous Janus nanomotors for active cargo delivery. *J. Am. Chem. Soc.* **137**, 4976–4979 (2015).
49. Solovev, A. A., Sanchez, S., Pumera, M., Mei, Y. F. & Schmidt, O. C. Magnetic control of tubular catalytic microbots for the transport, assembly, and delivery of micro-objects. *Adv. Funct. Mater.* **20**, 2430–2435 (2010).
50. Wang, Q. et al. Ultrasound Doppler-guided real-time navigation of a magnetic microswarm for active endovascular delivery. *Sci. Adv.* **7**, eabe5914 (2021).
51. Ye, Z. et al. Supramolecular modular assembly of imaging-trackable enzymatic nanomotors. *Angew. Chem. Int. Ed.* **63**, e202401209 (2024).
52. Zheng, S. et al. Biocompatible nanomotors as active diagnostic imaging agents for enhanced magnetic resonance imaging of tumor tissues in vivo. *Adv. Funct. Mater.* **31**, 2100936 (2021).
53. Vilela, D. et al. Medical imaging for the tracking of micromotors. *ACS Nano* **12**, 1220–1227 (2018).
54. Hortelao, A. C. et al. Swarming behavior and in vivo monitoring of enzymatic nanomotors within the bladder. *Sci. Robot.* **6**, eabd2823 (2021).
55. Wu, Z. et al. A microrobotic system guided by photoacoustic computed tomography for targeted navigation in intestines in vivo. *Sci. Robot.* **4**, eaax0613 (2019).
56. Simó, C. et al. Urease-powered nanobots for radionuclide bladder cancer therapy. *Nat. Nanotechnol.* **19**, 554–564 (2024).
The therapeutic use of enzyme-powered nanomotors with radionuclide payloads in vivo, marking a translational milestone.
57. Chen, S. et al. Dual-source powered nanomotor with integrated functions for cancer photo-theranostics. *Biomaterials* **288**, 121744–121753 (2022).
58. Yan, X. et al. Multifunctional biohybrid magnetite microrobots for imaging-guided therapy. *Sci. Robot.* **2**, eaaq1155 (2017).
59. Soler, L., Magdanz, V., Fomin, V. M., Sanchez, S. & Schmidt, O. G. Self-propelled micromotors for cleaning polluted water. *ACS Nano* **7**, 9611–9620 (2013).
A demonstration of self-propelled micromotors for the efficient oxidation of organic pollutants by improving intermixing in liquids.
60. Orozco, J. et al. Artificial enzyme-powered microfish for water-quality testing. *ACS Nano* **7**, 818–824 (2013).
61. Villa, K., Parmar, J., Vilela, D. & Sánchez, S. Metal-oxide-based microjets for the simultaneous removal of organic pollutants and heavy metals. *ACS Appl. Mater. Interfaces* **10**, 20478–20486 (2018).
62. Villa, K. et al. Visible-light-driven single-component $BiVO_4$ micromotors with the autonomous ability for capturing microorganisms. *ACS Nano* **13**, 8135–8145 (2019).
63. Ye, H. et al. Atomic H* mediated fast decontamination of antibiotics by bubble-propelled magnetic iron-manganese oxides core-shell micromotors. *Appl. Catal. B* **314**, 121484 (2022).
64. Chen, C., Ding, S. & Wang, J. Materials consideration for the design, fabrication and operation of microscale robots. *Nat. Rev. Mater.* **9**, 159–172 (2024).
65. Wang, Y. et al. Swarm autonomy: from agent functionalization to machine intelligence. *Adv. Mater.* **37**, 202312956 (2024).
66. Zhang, Y. & Hess, H. Chemically-powered swimming and diffusion in the microscopic world. *Nat. Rev. Chem.* **5**, 500–510 (2021).
67. Chen, S., Prado-Morales, C., Sánchez-DeAlcázar, D. & Sánchez, S. Enzymatic micro/nanomotors in biomedicine: from single motors to swarms. *J. Mater. Chem. B* **12**, 2711–2719 (2024).
68. Wang, Q., Yang, S. & Zhang, L. Untethered micro/nanorobots for remote sensing: toward intelligent platform. *Nano Micro Lett.* **16**, 40 (2024).
69. Dutta, S. et al. Recent developments in metallic degradable micromotors for biomedical and environmental remediation applications. *Nano Micro Lett.* **16**, 1–35 (2023).
70. Yang, L. et al. Autonomous environment-adaptive microrobot swarm navigation enabled by deep learning-based real-time distribution planning. *Nat. Mach. Intell.* **4**, 480–493 (2022).
A breakthrough in microrobot swarm navigation by integrating machine learning for environment-adaptive reconfiguration, thereby connecting computational intelligence to microrobot swarming.
71. Ghosh, A. et al. Helical nanomachines as mobile viscometers. *Adv. Funct. Mater.* **28**, 1705687 (2018).

72. Patiño, T., Llacer-Wintle, J., Pujals, S., Albertazzi, L. & Sánchez, S. Unveiling protein corona formation around self-propelled enzyme nanomotors by nanoscopy. *Nanoscale* **16**, 2904–2912 (2023).
73. Dasgupta, D. et al. Mobile nanobots for prevention of root canal treatment failure. *Adv. Healthc. Mater.* **11**, 2200232 (2022).
74. Dasgupta, D., Pally, D., Saini, D. K., Bhat, R. & Ghosh, A. Nanomotors sense local physicochemical heterogeneities in tumor microenvironments. *Angew. Chem. Int. Ed.* **59**, 23690–23696 (2020).
75. Gao, C., Zhou, C., Lin, Z., Yang, M. & He, Q. Surface wettability-directed propulsion of glucose-powered nanoflask motors. *ACS Nano* **13**, 12758–12766 (2019).
76. Simmchen, J. et al. Topographical pathways guide chemical microswimmers. *Nat. Commun.* **7**, 10598 (2016).
77. Blanchard, A. T. et al. Highly polyvalent DNA motors generate 100+ pN of force via autochemophoresis. *Nano Lett.* **19**, 6977–6986 (2019).
78. Ma, X. et al. Enzyme-powered hollow mesoporous Janus nanomotors. *Nano Lett.* **15**, 7043–7050 (2015).
79. Patiño, T. et al. Influence of enzyme quantity and distribution on the self-propulsion of non-Janus urease-powered micromotors. *J. Am. Chem. Soc.* **140**, 7896–7903 (2018).
80. Singh, D. P. et al. Interface-mediated spontaneous symmetry breaking and mutual communication between drops containing chemically active particles. *Nat. Commun.* **11**, 2210 (2020).
81. Venugopalan, P. L. et al. Conformal cytocompatible ferrite coatings facilitate the realization of a nanovoyager in human blood. *Nano Lett.* **14**, 1968–1975 (2014).
82. Venugopalan, P. L., Jain, S., Shivashankar, S. & Ghosh, A. Single coating of zinc ferrite renders magnetic nanomotors therapeutic and stable against agglomeration. *Nanoscale* **10**, 2327–2332 (2018).
83. Zhang, L. et al. Artificial bacterial flagella: fabrication and magnetic control. *Appl. Phys. Lett.* **94**, 064107 (2009).
84. Kadiri, V. M. et al. Biocompatible magnetic micro- and nanodevices: fabrication of FePt nanopropellers and cell transfection. *Adv. Mater.* **32**, 2001114 (2020).
85. Peter, F. et al. Degradable and biocompatible magnesium zinc structures for nanomedicine: magnetically actuated liposome microcarriers with tunable release. *Adv. Funct. Mater.* **34**, 2314265 (2024).
86. Wilson, D., Nolte, R. & van Hest, J. Autonomous movement of platinum-loaded stomatocytes. *Nat. Chem.* **4**, 268–274 (2012).
87. Liang, Z. & Fan, D. Visible light-gated reconfigurable rotary actuation of electric nanomotors. *Sci. Adv.* **4**, eaau0981 (2018).
88. Liang, Z., Teal, D. & Fan, D. Light programmable micro/nanomotors with optically tunable in-phase electric polarization. *Nat. Commun.* **10**, 5275 (2019).
89. Liang, Z., Joh, H., Lian, B., Fan, D. E. & Fan, D. E. Light-stimulated micromotor swarms in an electric field with accurate spatial, temporal, and mode control. *Sci. Adv.* **9**, eadi9932 (2023).
90. Zhang, J. et al. Light-powered, fuel-free oscillation, migration, and reversible manipulation of multiple cargo types by micromotor swarms. *ACS Nano* **17**, 251–262 (2023).
91. Li, W. et al. Arbitrary construction of versatile NIR-driven microrobots. *Adv. Mater.* **36**, 2402482 (2024).
92. Crosby, G. A., Watts, R. J. & Carstens, D. H. W. Inversion of excited states of transition-metal complexes. *Science* **170**, 1195–1196 (1970).
93. Zhou, J., Liu, Q., Feng, W., Sun, Y. & Li, F. Upconversion luminescent materials: advances and applications. *Chem. Rev.* **115**, 395–465 (2015).
94. Dey, K. K. et al. Micromotors powered by enzyme catalysis. *Nano Lett.* **15**, 8311–8315 (2015).
95. Pantarotto, D., Browne, W. R. & Feringa, B. L. Autonomous propulsion of carbon nanotubes powered by a multienzyme ensemble. *Chem. Commun.* **44**, 1533–1535 (2008).
96. Somasundar, A. et al. Positive and negative chemotaxis of enzyme-coated liposome motors. *Nat. Nanotechnol.* **14**, 1129–1134 (2019).
97. Joseph, A. et al. Chemotactic synthetic vesicles: design and applications in blood-brain barrier crossing. *Sci. Adv.* **3**, e1700362 (2017).
98. Agudo-Canalejo, J., Illien, P. & Golestanian, R. Phoresis and enhanced diffusion compete in enzyme chemotaxis. *Nano Lett.* **18**, 2711–2717 (2018).
99. Zhao, X. et al. Substrate-driven chemotactic assembly in an enzyme cascade. *Nat. Chem.* **10**, 311–317 (2018).
100. Arqué, X. et al. Intrinsic enzymatic properties modulate the self-propulsion of micromotors. *Nat. Commun.* **10**, 2826 (2019).
101. Pumm, A. K. et al. A DNA origami rotary ratchet motor. *Nature* **607**, 492–498 (2022).
102. Tran, M. P. et al. Genetic encoding and expression of RNA origami cytoskeletons in synthetic cells. *Nat. Nanotechnol.* **20**, 664–671 (2025).
103. Yang, L., Yu, J. & Zhang, L. Statistics-based automated control for a swarm of paramagnetic nanoparticles in 2-D space. *IEEE Trans. Robot.* **36**, 254–270 (2020).
104. Rückner, G. & Kapral, R. Chemically powered nanodimers. *Phys. Rev. Lett.* **98**, 150603 (2007).
105. Thakur, S., Chen, J. X. & Kapral, R. Interaction of a chemically propelled nanomotor with a chemical wave. *Angew. Chem. Int. Ed.* **50**, 10165–10169 (2011).
106. De Corato, M. et al. Self-propulsion of active colloids via ion release: theory and experiments. *Phys. Rev. Lett.* **124**, 108001 (2020).
107. Golestanian, R. Anomalous diffusion of symmetric and asymmetric active colloids. *Phys. Rev. Lett.* **102**, 188305 (2009).
108. Liebchen, B., Marenduzzo, D., Pagonabarraga, I. & Cates, M. E. Clustering and pattern formation in chemorepulsive active colloids. *Phys. Rev. Lett.* **115**, 258301 (2015).
109. Das, S. et al. Boundaries can steer active Janus spheres. *Nat. Commun.* **6**, 8999 (2015).
110. Palacios, L. S. et al. Guided accumulation of active particles by topological design of a second-order skin effect. *Nat. Commun.* **12**, 4691 (2021).
111. Saha, S., Ramaswamy, S. & Golestanian, R. Pairing, waltzing and scattering of chemotactic active colloids. *New J. Phys.* **21**, 063006 (2019).
112. Meredith, C. H. et al. Predator–prey interactions between droplets driven by non-reciprocal oil exchange. *Nat. Chem.* **12**, 1136–1142 (2020).
113. Soto, R. & Golestanian, R. Self-assembly of catalytically active colloidal molecules: tailoring activity through surface chemistry. *Phys. Rev. Lett.* **112**, 068301 (2014).
114. Mandal, N. S., Sen, A. & Astumian, R. D. A molecular origin of non-reciprocal interactions between interacting active catalysts. *Chem* **10**, 1147–1159 (2024).
115. Tucci, G. et al. Nonreciprocal collective dynamics in a mixture of phoretic Janus colloids. *New J. Phys.* **26**, 073006 (2024).
116. Agudo-Canalejo, J. & Golestanian, R. Active phase separation in mixtures of chemically interacting particles. *Phys. Rev. Lett.* **123**, 018101 (2019).
117. Golestanian, R. in *Active Matter and Nonequilibrium Statistical Physics: Lecture Notes of the Les Houches Summer School* Vol. 112 (eds Tailleur, J. et al.) 230–293 (Oxford Academic, 2022).
118. Wang, Q. et al. Tracking and navigation of a microswarm under laser speckle contrast imaging for targeted delivery. *Sci. Robot.* **9**, eadh1978 (2024).
119. Jin, D. et al. Swarming self-adhesive microgels enabled aneurysm on-demand embolization in physiological blood flow. *Sci. Adv.* **9**, eadf9278 (2023).

120. Ahmed, D. et al. Bioinspired acousto-magnetic microswarm robots with upstream motility. *Nat. Mach. Intell.* **3**, 116–124 (2021).
121. Palacci, J. et al. Artificial rheotaxis. *Sci. Adv.* **1**, e1400214 (2015).
122. Ren, L. et al. Rheotaxis of bimetallic micromotors driven by chemical-acoustic hybrid power. *ACS Nano* **11**, 10591–10598 (2017).
123. Choi, H., Cho, S. H. & Hahn, S. K. Urease-powered polydopamine nanomotors for intravesical therapy of bladder diseases. *ACS Nano* **14**, 6683–6692 (2020).
124. Wu, Z. et al. A swarm of slippery micropropellers penetrates the vitreous body of the eye. *Sci. Adv.* **4**, eaat4388 (2018).
125. Xu, C. et al. Magnesium-based micromotors as hydrogen generators for precise rheumatoid arthritis therapy. *Nano Lett.* **21**, 1982–1991 (2021).
126. Zhang, F. et al. Biohybrid microrobots locally and actively deliver drug-loaded nanoparticles to inhibit the progression of lung metastasis. *Sci. Adv.* **10**, eadn6157 (2024).
127. Arqué, X. et al. Autonomous treatment of bacterial infections in vivo using antimicrobial micro- and nanomotors. *ACS Nano* **16**, 7547–7558 (2022).
128. Ji, X. et al. Multifunctional parachute-like nanomotors for enhanced skin penetration and synergistic antifungal therapy. *ACS Nano* **15**, 14218–14228 (2021).
129. Dey, K. K. Dynamic coupling at low Reynolds number. *Angew. Chem. Int. Ed.* **58**, 2208–2228 (2019).
130. Maiti, A., Koyano, Y., Kitahata, H. & Dey, K. K. Activity-induced diffusion recovery in crowded colloidal suspensions. *Phys. Rev. E* **109**, 054607 (2024).
131. Pal, M. et al. Maneuverability of magnetic nanomotors inside living cells. *Adv. Mater.* **30**, 1800429 (2018).
132. Aghakhani, A. et al. High shear rate propulsion of acoustic microrobots in complex biological fluids. *Sci. Adv.* **8**, eabm5126 (2022).
133. Osat, S. & Golestanian, R. Non-reciprocal multifarious self-organization. *Nat. Nanotechnol.* **18**, 79–85 (2022).
134. Manna, R. K., Gentile, K., Shklyaev, O. E., Sen, A. & Balazs, A. C. Self-generated convective flows enhance the rates of chemical reactions. *Langmuir* **38**, 1432–1439 (2022).
135. Ma, X., Wang, X., Hahn, K. & Sánchez, S. Motion control of urea-powered biocompatible hollow microcapsules. *ACS Nano* **10**, 3597–3605 (2016).
136. Mehta, P., Lang, A. H. & Schwab, D. J. Landauer in the age of synthetic biology: energy consumption and information processing in biochemical networks. *J. Stat. Phys.* **162**, 1153–1166 (2016).
137. Jahnke, K. et al. DNA origami signaling units transduce chemical and mechanical signals in synthetic cells. *Adv. Funct. Mater.* **34**, 2301176 (2024).
138. Zhang, F. et al. ACE2 receptor-modified algae-based microrobot for removal of SARS-CoV-2 in wastewater. *J. Am. Chem. Soc.* **143**, 12194–12201 (2021).
139. Yuan, X., Ferrer-Campos, R., Garcés-Pineda, F. A. & Villa, K. Molecular imprinted $BiVO_4$ microswimmers for selective target recognition and removal. *Small* **19**, 2207303 (2023).
140. Yuan, X. et al. Self-degradable photoactive micromotors for inactivation of resistant bacteria. *Adv. Opt. Mater.* **12**, 2303137 (2024).
141. Guix, M. et al. Superhydrophobic alkanethiol-coated microsubmarines for effective removal of oil. *ACS Nano* **6**, 4445–4451 (2012).
142. Ferrer Campos, R., Bachimanchi, H., Volpe, G. & Villa, K. Bubble-propelled micromotors for ammonia generation. *Nanoscale* **15**, 15785–15793 (2023).
143. Ferrer Campos, R. et al. Boosting the efficiency of photoactive rod-shaped nanomotors via magnetic field-induced charge separation. *ACS Appl. Mater. Interfaces* **16**, 30077–30087 (2024).
144. Parmar, J. et al. Reusable and long-lasting active microcleaners for heterogeneous water remediation. *Adv. Funct. Mater.* **26**, 4152–4161 (2016).
145. Vilela, D., Guix, M., Parmar, J., Blanco-Blanes, À. & Sánchez, S. Micromotor-in-sponge platform for multicycle large-volume degradation of organic pollutants. *Small* **18**, 2107619 (2022).
146. Zhang, S. et al. 3D-printed micrometer-scale wireless magnetic cilia with metachronal programmability. *Sci. Adv.* **9**, eadf9462 (2023).
147. Tottori, S. et al. Magnetic helical micromachines: fabrication, controlled swimming, and cargo transport. *Adv. Mater.* **24**, 811–816 (2012).
The demonstration of two-photon laser-printed microrobots.
148. Hsu, L. Y. et al. Alignment and actuation of liquid crystals via 3D confinement and two-photon laser printing. *Sci. Adv.* **10**, 2597 (2024).
149. Melde, K. et al. Ultrasound-assisted tissue engineering. *Nat. Rev. Bioeng.* **2**, 486–500 (2024).
150. Kriebisch, C. M. E. et al. A roadmap toward the synthesis of life. *Chem* **11**, 102399 (2025).
151. Balazs, A. C., Fischer, P. & Sen, A. Intelligent nano/micromotors: using free energy to fabricate organized systems driven far from equilibrium. *Acc. Chem. Res.* **51**, 2979 (2018).
152. Song, J., Shklyaev, O. E., Sapre, A., Balazs, A. C. & Sen, A. Self-propelling macroscale sheets powered by enzyme pumps. *Angew. Chem. Int. Ed.* **136**, e202311556 (2024).
153. Gao, W. et al. Artificial micromotors in the mouse's stomach: a step toward in vivo use of synthetic motors. *ACS Nano* **9**, 117–123 (2015).
154. Li, J. et al. Enteric micromotor can selectively position and spontaneously propel in the gastrointestinal tract. *ACS Nano* **10**, 9536–9542 (2016).
155. De Ávila, B. E. F. et al. Micromotor-enabled active drug delivery for in vivo treatment of stomach infection. *Nat. Commun.* **8**, 272 (2017).
156. Zhang, F. et al. Nanoparticle-modified microrobots for in vivo antibiotic delivery to treat acute bacterial pneumonia. *Nat. Mater.* **21**, 1324–1332 (2022).
Biohybrid microrobots for the active delivery of antibiotics in the lungs in vivo, demonstrating notable potential for clinical applications in intensive care units.
157. Su, L. et al. Modularized microrobot with lock-and-detachable modules for targeted cell delivery in bile duct. *Sci. Adv.* **9**, eadj0883 (2023).
158. Feng, Y. et al. Directed neural stem cells differentiation via signal communication with Ni–Zn micromotors. *Adv. Mater.* **35**, 2301736 (2023).
159. Choi, H. et al. Urease-powered nanomotor containing STING agonist for bladder cancer immunotherapy. *Nat. Commun.* **15**, 9934 (2024).
160. Gao, C. et al. Light-driven artificial cell micromotors for degenerative knee osteoarthritis. *Adv. Mater.* **37**, 2416349 (2025).
161. Kagan, D. et al. Chemical sensing based on catalytic nanomotors: motion-based detection of trace silver. *J. Am. Chem. Soc.* **131**, 12082–12083 (2009).
162. Campuzano, S. et al. Bacterial isolation by lectin-modified microengines. *Nano Lett.* **12**, 396–401 (2012).
163. Li, J. et al. Water-driven micromotors for rapid photocatalytic degradation of biological and chemical warfare agents. *ACS Nano* **8**, 11118–11125 (2014).
164. Gao, L., Giglio, K. M., Nelson, J. L., Sondermann, H. & Travis, A. J. Ferromagnetic nanoparticles with peroxidase-like activity enhance the cleavage of biological macromolecules for biofilm elimination. *Nanoscale* **6**, 2588–2593 (2014).

165. Vilela, D., Parmar, J., Zeng, Y., Zhao, Y. & Sánchez, S. Graphene-based microbots for toxic heavy metal removal and recovery from water. *Nano Lett.* **16**, 2860–2866 (2016).
166. Jurado-Sánchez, B., Pacheco, M., Rojo, J. & Escarpa, A. Magnetocatalytic graphene quantum dots Janus micromotors for bacterial endotoxin detection. *Angew. Chem. Int. Ed.* **56**, 6957–6961 (2017).
167. Villa, K., Děkanovský, L., Plutnar, J., Kosina, J. & Pumera, M. Swarming of perovskite-like Bi_2WO_6 microrobots destroy textile fibers under visible light. *Adv. Funct. Mater.* **30**, 2007073 (2020).
168. Mou, F. et al. ZnO-based micromotors fueled by CO_2: the first example of self-reorientation-induced biomimetic chemotaxis. *Natl Sci. Rev.* **8**, nwab066 (2021).
169. Urso, M., Ussia, M., Novotný, F. & Pumera, M. Trapping and detecting nanoplastics by MXene-derived oxide microrobots. *Nat. Commun.* **13**, 3573(2022).
170. Patiño, T. et al. Synthetic DNA-based swimmers driven by enzyme catalysis. *J. Am. Chem. Soc.* **146**, 12664–12671 (2024).

Acknowledgements

S.S. acknowledges funding from the European Research Council (ERC) under the European Union's Horizon 2020 and Horizon Europe research and innovation programmes (grant agreement numbers 866348, i-NanoSwarms, and 101138723, MucOncoBots, 101189423, OrthoBots) and from 'la Caixa' Foundation under the grant agreement LCF/PR/HR21/52410022. A.S. thanks S. Sen for many stimulating discussions. A.S. also acknowledges funding by the National Science Foundation, the Air Force Office of Scientific Research, the Defense Threat Reduction Agency, the Charles E. Kaufman Foundation and the Alfred P. Sloan Foundation. J.T. thanks the funding support from the Hong Kong Research Grants Council (RGC) (C7082-21G). L.Z. thanks funding support from the Hong Kong Research Grants Council RGC (R4015-2, RFS2122-4S03, STG1/E-401/23-N). W.W. thanks the National Natural Science Foundation of China (grant number T2322006). K.V. acknowledges funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (GA number 101076680; PhotoSwim) and the grant PID2022-136886OA-I00 financed by MCIN/AEI/10.13039/501100011033/ FEDER, UE. H.H. gratefully acknowledges support from NSF grant 2230116 and ARO grant W911NF-22-1-0047. R.G. acknowledges support from the Max Planck School Matter to Life and the MaxSynBio Consortium, which are jointly funded by the Federal Ministry of Education and Research (BMBF) of Germany and the Max Planck Society. A.G. thanks the Wellcome Trust/DBT India Alliance Fellowships/Grants (grant number IA/S/19/2/504655). D.E.F. thanks the support of the National Science Foundation (2219221 and 1930649). S.C. acknowledges the Predoctoral AGAUR-FI Joan Oró grant (2023 FI-1 00654) funded by 'Secretaria d'Universitats i Recerca del Departament de Recerca i Universitats de la Generalitat de Catalunya' and by European Social Fund Plus.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence should be addressed to Ayusman Sen or Samuel Sánchez.

Peer review information *Nature Nanotechnology* thanks Motilal Mathesh and Fei Peng for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

[1]Institute for Bioengineering of Catalonia (IBEC), The Barcelona Institute for Science and Technology (BIST), Barcelona, Spain. [2]Faculty of Physics, University of Barcelona, Barcelona, Spain. [3]Materials Science and Engineering Program, Texas Materials Institute, The University of Texas at Austin, Austin, TX, USA. [4]Walker Department of Mechanical Engineering, The University of Texas at Austin, Austin, TX, USA. [5]Max Planck Institute for Medical Research, Heidelberg, Germany. [6]Institute for Molecular Systems Engineering and Advanced Materials, Universität Heidelberg, Heidelberg, Germany. [7]Center for Nanomedicine, Institute for Basic Science (IBS), Seoul, Republic of Korea. [8]Department of Nano Biomedical Engineering (NanoBME), Advanced Science Institute, Yonsei University, Seoul, Republic of Korea. [9]Department of Physics, Indian Institute of Science, Bangalore, India. [10]Centre for Nano Science and Engineering, Indian Institute of Science, Bangalore, India. [11]Center for Molecular Biology of Heidelberg University (ZMBH), Heidelberg University, Heidelberg, Germany. [12]Max Planck Institute for Dynamics and Self-Organization (MPI-DS), Göttingen, Germany. [13]Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford, UK. [14]Department of Biomedical Engineering, Columbia University, New York, NY, USA. [15]School of Integrated Circuits, Harbin Institute of Technology (Shenzhen), Shenzhen, China. [16]Sauvage Laboratory for Smart Materials, Harbin Institute of Technology (Shenzhen), Shenzhen, China. [17]Multi-Scale Robotics Lab, Institute of Robotics and Intelligent Systems, ETH Zurich, Zurich, Switzerland. [18]Biomedical Engineering Department, Institute for Complex Molecular Systems, Technische Universiteit Eindhoven, Eindhoven, The Netherlands. [19]Department of Chemistry, The University of Hong Kong, Hong Kong, China. [20]Institute of Chemical Research of Catalonia (ICIQ), The Barcelona Institute of Science and Technology (BIST), Tarragona, Spain. [21]School of Materials Science and Engineering, Harbin Institute of Technology (Shenzhen), Shenzhen, China. [22]Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Hong Kong, China. [23]Department of Chemistry, The Pennsylvania State University, University Park, PA, USA. [24]Department of Chemical Engineering, The Pennsylvania State University, University Park, PA, USA. [25]Department of Materials Science and Engineering, The Pennsylvania State University, University Park, PA, USA. [26]Catalan Institute for Research and Advanced Studies (ICREA), Barcelona, Spain. ✉e-mail: asen@psu.edu; ssanchez@ibecbarcelona.eu