Current Robotics Reports (2022) 3:127–137
https://doi.org/10.1007/s43154-022-00085-6

NANOROBOTICS AND MICROROBOTICS (A FERREIRA, SECTION EDITOR)

Check for updates

Magnetic Microrobotic Swarms in Fluid Suspensions

Hui Chen[1,2] · **Jiangfan Yu**[1,2]

Accepted: 30 June 2022 / Published online: 5 August 2022

Abstract

Purpose of Review Microrobotic swarms have attracted extensive attentions due to their potential in medical and bioengineering applications. Because of the small sizes of swarm agents, integrating actuators, sensors, and control circuits are difficult. Microrobotic swarms in different fluid environments should be actuated and navigated by external physical fields, chemical fuels, and biological power. Magnetic fields have advantages, including real-time control, programmability, and high penetrability, and thus they are widely used to actuate magnetic microrobotic swarms. This review summarizes the recent remarkable progress in the magnetic actuation and navigation of magnetic microrobotic swarms.

Recent Findings After development and evolution, the design of magnetic agents, and techniques of magnetic actuation and automatic control are now in place. Magnetic microrobotic swarms formed by different agents have been proposed, such as nanoparticles, artificial bacterial flagella, and bacteria. By tuning the applied fields, the morphology, orientation, and position of swarms can be adjusted on demand. Reconfigurability and motion dexterity are endowed to the microrobotic swarms.

Summary The wireless magnetic actuation systems for microrobotic swarms are introduced, and the characteristics of microrobotic swarms actuated by different customized magnetic fields are described, such as rotating, oscillating, and hybrid fields. The results show that the swarm intelligence has been enhanced. Finally, the current challenges and opportunities in this field are discussed. The developments in materials, actuation methods, control strategies, and imaging modalities will transform the magnetic microrobotic swarms from lab to practical clinic.

Keywords Hybrid field · Magnetic actuation · Magnetic field · Microrobotic swarms · Oscillating field · Rotating field

Introduction

Over the past decade, there has been an increasing interest in microrobotic swarms at small scales [1]. The swarms are formed by thousands or even millions of small individual agents [2]. Tasks that are challenging for single agent can be accomplished by swarms collectively, such as targeted delivery and hyperthermia [3]. The imaging contrast is enhanced by using the swarms, benefiting the image-guided navigation and manipulation [4]. The swarms also have high environmental adaptability by regulating their morphology in response to environmental stimuli [5].

Due to the small sizes of agents, the traditional internal energy storage devices cannot be integrated, and external physical fields have been used to energize the agents wirelessly, such as magnetic fields, optical fields, acoustic fields, and electric fields [6, 7]. Chemical fuels and biological power are also exploited to propel the swarms [8]. Magnetic fields serving as one of the actuation methods can control the agents in real time, and the dexterous and precise control capabilities are endowed to the microrobotic swarms [1]. Meanwhile, the magnetic fields cause negligible effects on human bodies and can penetrate deep tissues, which further expand the applications of microrobotic swarms.

Recently, the microrobotic swarms driven by magnetic fields have been investigated in different aspects, ranging from the design of actuation methods and motion control algorithms to biomedical applications [9–11]. Using biocompatible and biodegradable materials, the cytotoxicity of swarms is reduced. By tuning parameters

This article is part of the Topical Collection on *Nanorobotics and Microrobotics*

✉ Jiangfan Yu
yujiangfan@cuhk.edu.cn

1 School of Science and Engineering, The Chinese University of Hong Kong, Shenzhen 518172, China

2 Shenzhen Institute of Artificial Intelligence and Robotics for Society, Shenzhen 518129, China

of the applied magnetic fields, the swarm patterns are adjusted for adapting tortuous environments, and thus, hard-to-reach regions are accessible [12]. With effective automatic control methods, the swarms can be propelled to move following desired trajectories [13]. Different imaging modalities, such as magnetic resonance imaging (MRI) [14], fluorescence imaging [15], and ultrasound imaging (US) [16], allow the swarms to be detected in vivo, and biomedical applications can be accomplished [3].

This review presents the recent progress of microrobotic swarms energized by magnetic fields. The magnetic actuation systems for microrobotic swarms are introduced. Then, we focus on the characteristics of swarms actuated by different magnetic fields, such as rotating, oscillating, and hybrid fields. Finally, we present the existing challenges and future opportunities of microrobotic swarms.

Magnetic Actuation

The magnetic fields have been widely employed as external power sources for actuating the microrobotic swarms. Herein, the mechanisms of the magnetic actuation are discussed, and different magnetic actuation systems are presented.

Magnetic Actuation Mechanisms

When the magnetic agents are placed in the external magnetic fields, the magnetic torque τ or magnetic force F will be imparted on them as [17, 18•]

$$\boldsymbol{\tau} = \mathbf{m} \times \mathbf{B} = \begin{bmatrix} 0 & -m_z & m_y \\ m_z & 0 & -m_x \\ -m_y & m_x & 0 \end{bmatrix} \mathbf{B} \tag{1}$$

$$\mathbf{F} = (\mathbf{m} \bullet \nabla)\mathbf{B} = \begin{bmatrix} \frac{\partial \mathbf{B}}{\partial x} & \frac{\partial \mathbf{B}}{\partial y} & \frac{\partial \mathbf{B}}{\partial z} \end{bmatrix}^{\mathrm{T}} \mathbf{m}, \tag{2}$$

where m is the magnetic moment of the agents and B is the magnetic flux density at the position of the agents. If the external magnetic fields are uniform, the agents will experience a magnetic torque when their easy magnetization axis are not aligned with the field direction. Therefore, the agents will rotate homogeneously, converting the magnetic energy to kinetic energy. When the magnetic agents are subject to a magnetic field gradient, they will be attracted to a region with high magnetic flux density by the magnetic force, which is influenced by multiple factors, including the magnetization and size of the agents, and the gradient of the fields.

Magnetic Actuation Systems

The magnetic actuation systems consisting of electromagnetic coils and permanent magnets have been investigated for generating uniform and gradient fields. The magnetic fields generated by the electromagnetic coils can be adjusted quickly, such as the magnitude and direction [19]. Meanwhile, magnetic fields in any direction can be realized based on the superposition of fields from different coils. As shown in Fig. 1(a), the Helmholtz coil is composed of three pairs of coaxial coils, where the currents flowing in coaxial coils have the same handedness. The generated fields at the center of the Helmholtz coil are almost uniform, and thus, the Helmholtz coil is suitable for magnetic torque control [20]. Apart from the static coils, the actuation system consisting of three mobile electromagnetic coils has been developed, named RoboMag (Fig. 1(b)) [21]. The working space of the mobile coils was larger than that of static coils as the position of the swarms can be tracked, and the collision among the three coils was avoided with optimization algorithms.

By considering permanent magnets as the source of magnetic fields, the actuation systems can provide large working space and high field strength [19]. A 50-mm-diameter sphere permanent magnet was used to gather magnetic nanoparticles into microrobotic swarms, which were navigated in a porcine coronary artery with flowing blood [22•]. The permanent magnets were also integrated into a rotational platform for actuating swarms, as shown in Fig. 1(c) [23]. The vibration was reduced by containing the magnets in a 3D-printed case. Meanwhile, the magnet arrays have been developed with discrete ferromagnets and wood jigs, which were operated wirelessly using a motorized platform (Fig. 1(d)) [24]. The desired magnetic potential energy maps were generated by adjusting the external magnet arrays, and thus, the magnetic agents distributed on the fluid–air interface can be attracted to the convergent fields, forming swarms with specific patterns.

Although some magnetic actuation systems have been developed, the actuation for microrobotic swarms in deep regions still is a challenge, as the field strength and gradient attenuate rapidly with the distance [25]. In this case, the external electromagnets and current in coils should be larger, where the cooling systems are required to dissipate the heat.

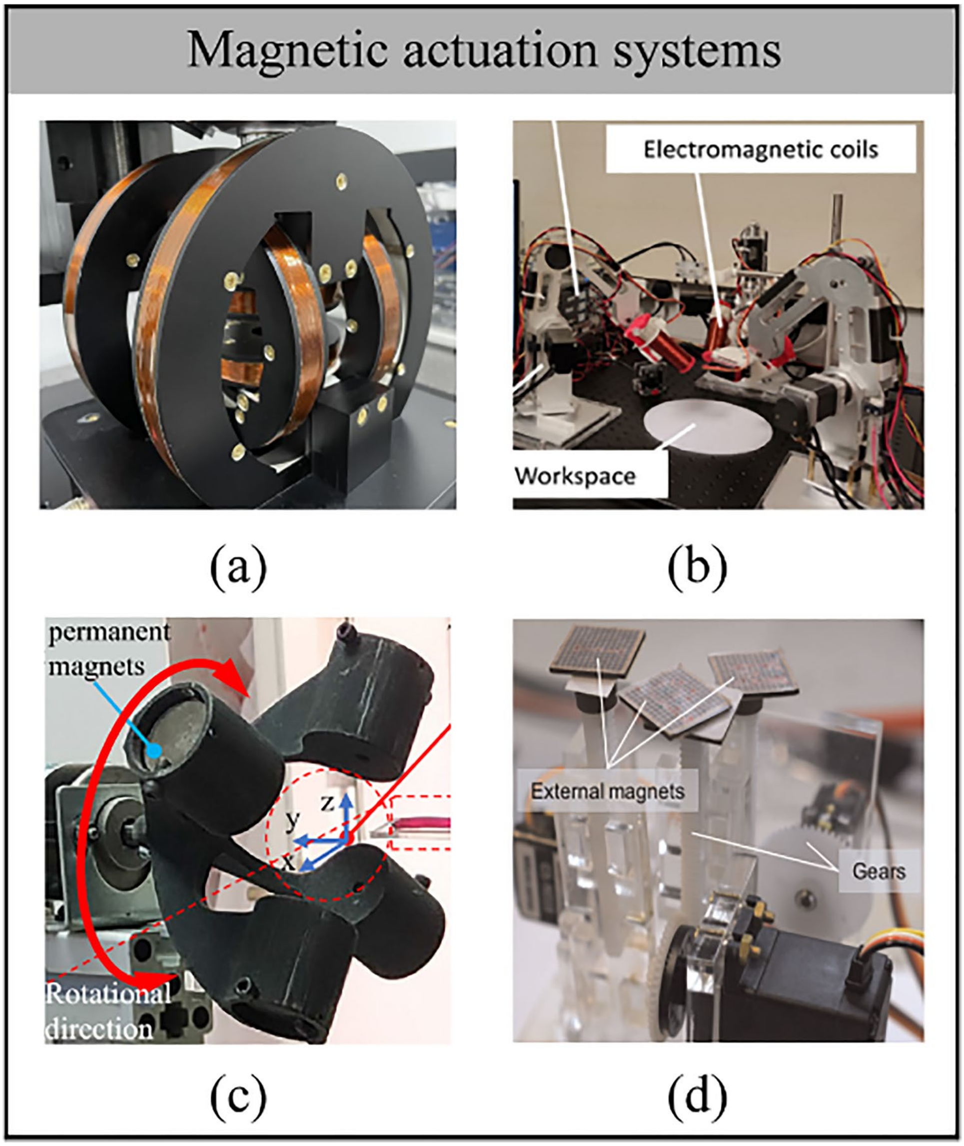

Fig. 1 Magnetic actuation systems. **a** Static Helmholtz coil. **b** Mobile electromagnetic coils with robotic arms. Adapted with permission from [21]. Copyright 2020 IEEE. **c** Rotational permanent magnets. Adapted with permission from [23]. Copyright 2021 IEEE. **d** Permanent magnet arrays. Adapted with permission from [24]. Copyright 2020 SAGE

Magnetic Fields for Actuating Microrobotic Swarms

Gradient Fields

Gradient fields are the inhomogeneous fields where the field strength varies with position, as shown in Fig. 2(a). When magnetic agents are placed in the gradient fields, they will be forced to move by the magnetic force. The gradient fields have been used to separate the microparticles of 0.2 μm and 1 μm in sizes in fluids [26]. The particles of 0.2 μm represented by green fluorescence moved to lower outlets of a microchannel, while the larger particles (1 μm) labeled by red color were mainly concentrated at the upper outlets (Fig. 2(b)). In de-ionized water, the iron oxide nanoparticles have been assembled into chain-like structures by applying an external gradient field (Fig. 2(c)) [27]. Meanwhile, Hwang et al. gathered the magnetic nanoparticles into a microrobotic swarm using a permanent magnet [28]. The suspended nanoparticles were attracted into the swarm by controlling the swarm to move following a preprogrammed trajectory, as shown in Fig. 2(d). Furthermore, multiple magnets can be programmed to generate desired magnetic potential energy maps spatially and temporally. Dong et al. realized static and time-varying generation of microrobotic swarms by programming the external magnetic force distribution [24]. The swarms had the capability of passing through tortuous environments by changing the morphology adaptively, and meanwhile, nonmagnetic objects with different shapes can be transported with suitable swarm patterns (Fig. 2(e)). Apart from the swarms consisting of artificial magnetic agents, the living organisms can also be assembled into swarms. Lanauze et al. achieved the aggregation of magnetotactic bacteria

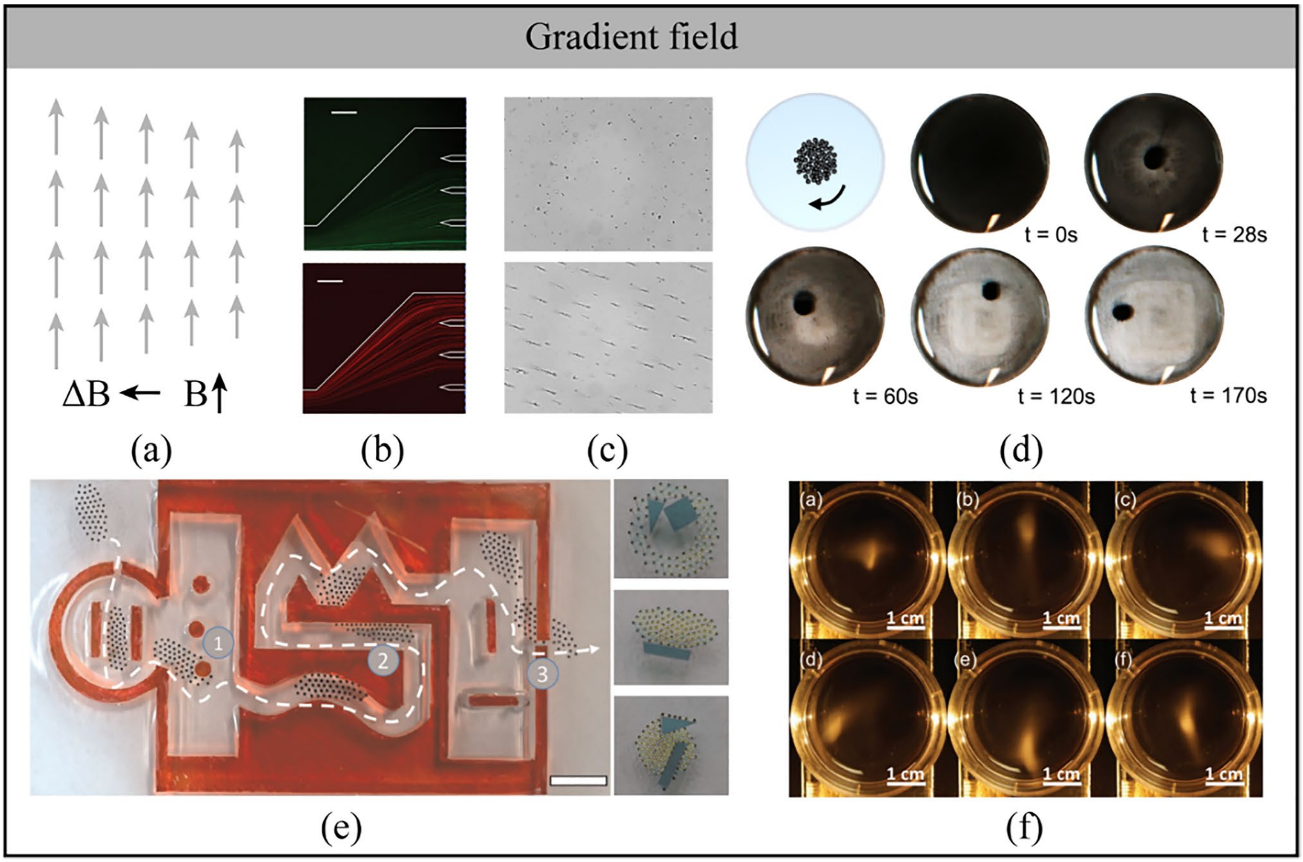

Fig. 2 Microrobotic swarms driven by gradient fields. **a** The schematic illustration of a gradient field. **b** Separation of nanoscale particles. The green and red fluorescence indicate the microparticles of 0.2 μm and 1 μm in sizes, respectively. Adapted with permission from [26]. Copyright 2021 The Royal Society of Chemistry. **c** Formation of chain-like structures. Adapted with permission from [27]. Copyright 2008 AIP. **d** Aggregation and locomotion of a circular swarm using a permanent magnet. Adapted with permission from [28]. Copyright 2019 AAAS. **e** Collective navigation and cargo transportation of microrobotic swarms. Adapted with permission from [24]. Copyright 2020 SAGE. **f** Locomotion of MTB swarms in a Petri dish. Adapted with permission from [29]. Copyright 2014 SAGE

MC-1 (MTB) based on the internal iron oxide nanoparticle chains [29]. When adjusting the magnetic field lines toward a convergence point in space, the moving direction of the bacteria would align with the field lines and the flagella will propel them to the convergence regions. Therefore, the MTB swarms can move to different parts of a Petri dish in a controlled manner (Fig. 2(f)).

Rotating Fields

Rotating field is a controllable homogeneous magnetic field with time-varying field direction (Fig. 3(a)). The agents in the rotating fields will experience a magnetic torque that attempts to align their magnetic components with the field lines, inducing the rotation motion [18•]. As shown in Fig. 3(b), Janus particles have been assembled into a swarm by applying the rotating magnetic fields [30]. Using the same fields, Yu et al. investigated the generation and locomotion of vortex-like microrobotic swarms consisting of paramagnetic nanoparticles [31]. When the distance between two independent swarms was less than a critical value, coaxial rotation and merging of the two swarms were triggered (Fig. 3(c)). Meanwhile, the vortex-like swarms can be navigated from the left original reservoir to the right target reservoir by passing through a confined channel. Apart from the spherical agents, the nanoparticles with other shapes also have been investigated for generating microrobotic swarms. As shown in Fig. 3(d), circular swarms formed by peanut-shaped hematite colloidal particles have been reported using the external rotating fields [32]. It is demonstrated that the swarms can be controlled to move following a desired trajectory, and a non-magnetic microsphere can be manipulated by the swarms collectively.

In addition, the screw-like artificial bacterial flagella (ABFs) also have been investigated for generating microrobotic swarms. Actuated by the rotating fields, the rotating motion along the longitudinal axis of the ABFs will be triggered, inducing movement of the ABFs. Microrobotic

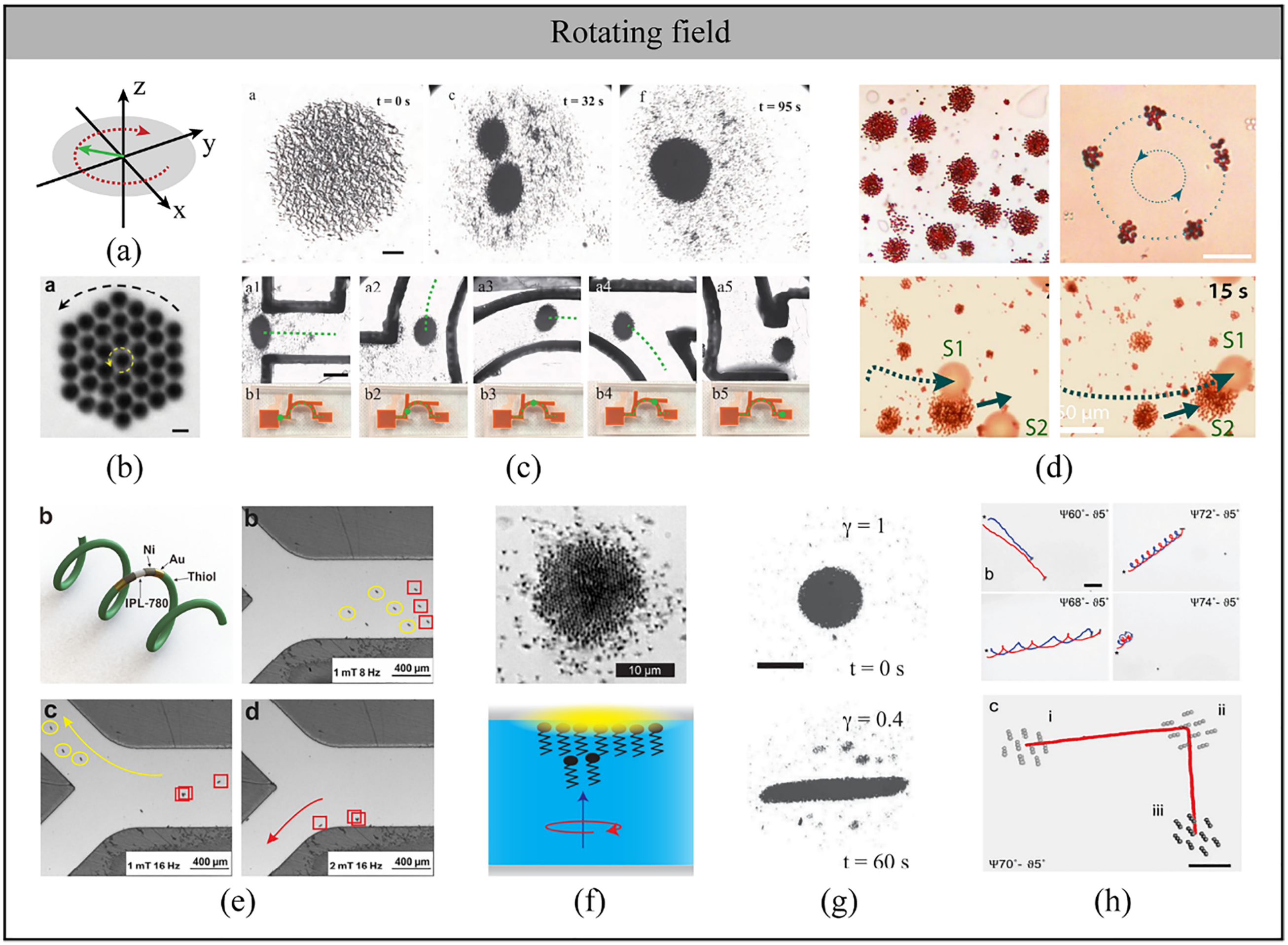

Fig. 3 Microrobotic swarms driven by rotating fields. **a** The schematic illustration of a rotating field. **b** A circular swarm formed by Janus particles. Adapted with permission from [30]. Copyright 2015 Wiley–VCH GmbH. c Merging of vortex-like swarms and navigation of the swarm in a curved channel. Adapted with permission from [31]. Copyright 2018 SAGE. d Swarm formation using peanut-shaped agents and cargo manipulation using the swarms. Adapted with permission from [32]. Copyright 2019 AAAS. e Artificial bacterial flagella swarms moving into different branches of a Y-shaped microchannel. Adapted with permission from [34]. Copyright 2018 American Chemical Society. f A circular swarm at the fluid–air interface. Adapted with permission from [35]. Copyright 2017 IOP. g Reconfiguration between elliptical swarms and vortex-like swarms. Adapted with permission from [36••]. Copyright 2021 IEEE. h Navigation of microrobotic swarms actuated by precessing magnetic fields. Adapted with permission from [37]. Copyright 2020 The Royal Society of Chemistry

swarms consisting of ABFs have been reported with the capability of swimming within an intraperitoneal cavity of mice [33]. Wang et al. fabricated surface-modified ABFs with different wettabilities, resulting in the change of step-out frequency (Fig. 3(e)) [34]. Specifically, when the surfaces of ABFs were hydrophobic, the step-out frequencies and maximum forward speed were larger compared with that of ABFs with hydrophilic surfaces. Therefore, by adjusting the frequency of the applied rotating fields, the swarms can be manipulated to move into different branches of a Y-shaped microchannel. Meanwhile, the microrobotic swarms have been formed at the fluid–air interface apart from the fluid–fluid environments. As shown in Fig. 3(f), the magnetic propellers were actuated to move upward and reached the fluid–air interface, generating a circular swarm with a boundary [35].

The rotating fields with changed field strength also have been investigated. Yu et al. reported the microrobotic swarms formed actuated by an elliptical rotating field, where the field strength changed periodically [36••]. With the applied elliptical rotating fields, the swarms shirked along the long axis of the field and elongated along the perpendicular direction, forming an elliptical pattern (Fig. 3(g)). The elliptical swarms can be transformed back to vortex-like swarms by adjusting the elliptical fields to the circular rotating fields. In addition, the rotating fields with two angles, a precession angle and a tilt angle, have been developed, named precessing fields [37]. Using the precessing fields,

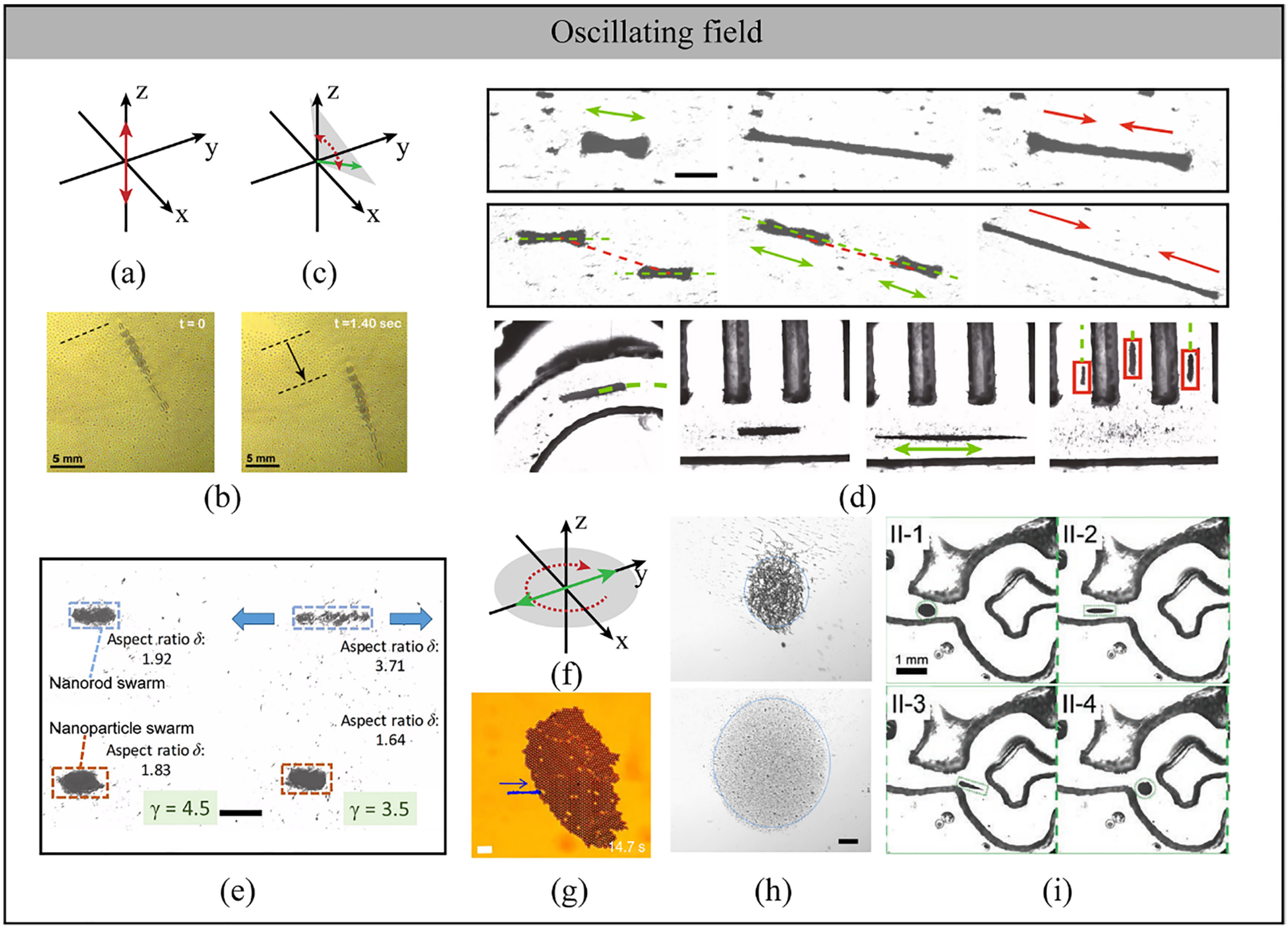

Fig. 4 Microrobotic swarms driven by oscillating fields. **a** The schematic illustration of a 1-D oscillating field. **b** A snake-like swarm moving at the fluid–air surface actuated by the 1-D oscillating fields. Adapted with permission from [39]. Copyright 2009 APS. **c** The schematic illustration of a 2-D oscillating field. **d** Elongation, shrinking, and locomotion of ribbon-like swarms actuated by the 2-D oscillating fields. Adapted with permission from [41]. Copyright 2018 Springer Nature. **e** Pattern reconfiguration of nanorod swarms compared with nanoparticle swarms actuated by the 2-D oscillating fields. Adapted with permission from [42]. Copyright 2021 American Chemical Society. **f** The schematic illustration of a 3-D oscillating field. **g** Locomotion of a carpet-like swarm actuated by the 3-D oscillating fields. Adapted with permission from [43]. Copyright 2019 Springer Nature. **h** Swarm spreading actuated by the 3-D oscillating fields. Adapted with permission from [44]. Copyright 2020 Elsevier. **i** Pattern transformation between a ribbon-like swarm and a vortex-like swarm for passing through a narrow channel. Adapted with permission from [45]. Copyright 2021 Wiley–VCH GmbH

the microparticle chains in swarms were actuated to rotate around the precession axis [37]. By tuning the tilt angle and the precession angle, the swarms shown different locomotion behaviors with trochoidal trajectories, and the trajectory tracking of the swarms can be achieved (Fig. 3(h)). Using the same precessing fields, the dynamic assembly of magnetic droplets containing microparticle chains was accomplished at the fluid–air interface [38]. The expansion and shrinking of the swarms were accomplished, and the swarms had the capability of moving with cargoes. Meanwhile, the peanut-shaped microparticles were energized to tumble by applying the precessing fields, forming ribbon-like swarms subjected to hydrodynamic and magnetic interactions [32]. Multiple microspheres were manipulated by the swarms in a large area synchronously.

Oscillating Fields

The oscillating magnetic fields are programmed with periodical change of field strength or direction. The 1-D oscillating magnetic field is shown in Fig. 4(a), whose field strength changes along one direction. Using the 1-D oscillating field, a snake-like microrobotic swarm was formed at the fluid–air interface with the capability of swimming on a straight line (Fig. 4(b)) [39]. The 2-D oscillating magnetic field is designed in a plane with simultaneously changed field strength and direction, as shown in Fig. 4(c). Between two immiscible liquids, i.e., the deep saturated solution of Na_2SO_4 in water and silicone oil, nickel microparticles were assembled into aster-like swarms by applying the 2-D oscillating fields [40]. It is demonstrated that the size of the

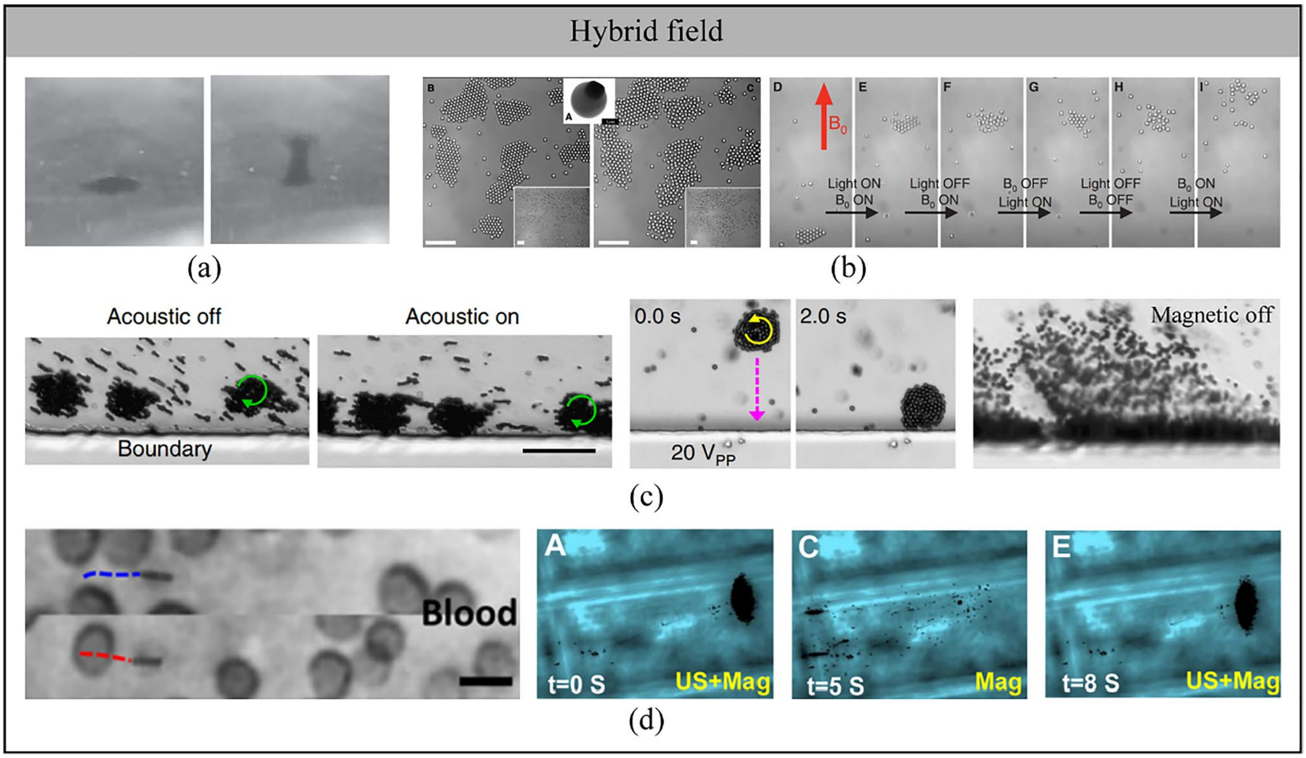

Fig. 5 Microrobotic swarms driven by hybrid fields. **a** A tornado-like swarm actuated by magnetic and optical fields. Adapted with permission from [46]. Copyright 2020 American Chemical Society. **b** Formation and locomotion of polymer microparticles driven by magnetic and optical fields. Adapted with permission from [47]. Copyright 2013 AAAS. **c** Assembly of magnetic microparticles and swarm locomotion actuated by magnetic and acoustic fields. The right image shows the disassembly of swarms when turning off the magnetic field. Adapted with permission from [48]. Copyright 2017 Springer Nature. **d** Microrobotic swarms actuated by magnetic and acoustic fields. The left image shows the movement of the agents in blood, where the blue and red lines are the trajectories of the agents by applying magnetic fields and acoustic fields, respectively. The right three images show the formation and locomotion of the swarms driven by hybrid fields. Adapted with permission from [49]. Copyright 2015 American Chemical Society

swarms increased when the applied frequency decreased. Yu et al. showed the reversible elongation and shrinking of ribbon-like swarms consisting of nanoparticles driven by the 2-D oscillating fields (Fig. 4(d)) [41]. Locomotion of the swarms was induced when the field plane tilted a small pitch angle to the substrate, and splitting of the swarms can be triggered on-demand. Using the same 2-D oscillating fields, a swarm of nickel nanorods was proposed and compared with the ribbon-like swarms formed by spherical nanoparticles [42]. When the field ratio was increased, the nanorod swarms were elongated while the aspect ratios of the nanoparticle swarms were reduced (Fig. 4(e)). Furthermore, the 3-D oscillating magnetic field is created by the combination of rotating fields and oscillating fields (Fig. 4(f)). Massana et al. investigated the generation and movement of carpet-like swarms formed by colloidal rollers using a 3-D oscillating field [43]. As the agents were coupled to the substrate, the rotational motion was transformed into translation, endowing the locomotion capability to the swarms (Fig. 4(g)). Apart from gathering, it is also demonstrated that the 3-D oscillating field can be designed to disassemble and spread the microrobotic swarms based on hydrodynamic drag and magnetic interactions (Fig. 4(h)) [44]. Meanwhile, the microrobotic swarms have the reconfiguration capability by switching the applied fields. When moving in a confined environment and encountering a narrow channel, the vortex-like swarm was transformed to a ribbon-like swarm to adapt to the environment by changing the rotating fields to oscillating fields (Fig. 4(i)) [45]. After passing the narrow region, the swarm pattern was transformed back to the circular shape for smooth steering motion.

Hybrid Fields

The hybrid fields are the combination of magnetic fields and other fields, such as optical fields and acoustic fields. One of the power sources always is used to induce the swarm generation, and another power for locomotion and reconfiguration according to task requirements. As shown in Fig. 5(a), paramagnetic nanoparticles were energized by the magnetic fields, forming a microrobotic swarm on the substrate, and then, the swarm swirled up

Table 1 Summary of microrobotic swarms driven by magnetic fields

Magnetic field types	Agents	Patterns	Environments	Refs
Gradient field	Iron oxide magnetic nanoparticles	Chain-like shape	Fluid	[27]
	Iron oxide magnetic nanoparticles	Circular shape	Fluid	[28]
	Neodymium–iron–boron alloy microparticles	Designed shapes	Fluid–air interface	[24]
	Magnetotactic bacteria	No specific shape	Fluid	[29]
Rotating field	Janus particles	Circular shape	Fluid	[30]
	Paramagnetic nanoparticles	Vortex-like shape	Fluid	[31]
	Peanut-shaped hematite colloidal particles	Vortex-like shape, Ribbon-like shape	Fluid	[32]
	Artificial bacterial flagella	No specific shape	Fluid	[33]
	Helical micropropellers	Circular shape	Fluid–air interface	[35]
	Paramagnetic nanoparticles	Elliptical shape	Fluid	[36••]
	Paramagnetic microparticles	No specific shape	Fluid	[37]
	Droplets containing microparticles	No specific shape	Fluid–air interface	[38]
Oscillating field	Sphere nickel microparticles	Snake-like shape	Fluid–air interface	[39]
	Ferromagnetic colloidal particles	Aster-like shape	Fluid–fluid interface	[40]
	Paramagnetic nanoparticles	Ribbon-like shape	Fluid	[41]
	Nickel nanorods	Ribbon-like shape	Fluid	[42]
	Colloidal particles	Carpet-like shape	Fluid	[43]
Hybrid field	Paramagnetic nanoparticles	Tornado-like shape	Fluid	[46]
	Colloidal particles	No specific shape	Fluid	[47]
	Superparamagnetic particles	Circular shape	Fluid	[48]
	Agents containing Au nanorod and Ni coated helical structure	No specific shape	Fluid	[49]

and was transformed into a tornado-like swarm with exposure to light [46]. Palacci et al. realized the formation of swarms consisting of photoactivated colloidal particles when a blue light was turned on (Fig. 5(b)) [47]. After the magnetic fields were applied, the swarms were propelled to move following the direction of the magnetic field with stable patterns (Fig. 5(b)), and the swarms dissolved when only magnetic fields was applied. Furthermore, the combination of magnetic and acoustic fields also has been investigated for actuating the microrobotic swarms. Ahmed et al. reported the aggregation of superparamagnetic particles with the applied magnetic fields [48], and rolling motion of the swarms near and far away from the boundaries by using the acoustic fields (Fig. 5(c)). It is also demonstrated that the swarms disassociated without the magnetic fields (Fig. 5(c)). Combined with magnetic and acoustic fields, the agents containing a helical structure and a nanorod were also actuated in blood (Fig. 5(d)) [49]. Directional motion of the swarms was observed when the acoustic fields were turned off, and the swarms were reformed after applying the acoustic fields again (Fig. 5(d)).

Despite the remarkable achievements of microrobotic swarms driven by magnetic fields, the swarm intelligence should be enhanced for expanding working dimensions. The design of magnetic agents, formation of swarms, and magnetic actuation systems are required to be further investigated.

Conclusion

To date, the research progress of magnetic microrobotic swarms has demonstrated that they can perform complex missions efficiently. This review summarizes the recent developments of microrobotic swarms driven by magnetic fields in fluid suspensions. Different wireless magnetic actuation systems are introduced. The swarms actuated by different magnetic fields are summarized, as shown in Table 1. The swarms have been endowed with different capabilities, such as active locomotion, pattern reconfiguration, and image-guided navigation. However, there are still restrictions hindering the further applications of microrobotic swarms, and breakthroughs are required.

Aiming at potential biomedical applications, the precisely controlled locomotion of microrobotic swarms in biological fluids is needed [50]. Physical features of bio-fluids, such as macromolecules and environmental boundaries, will influence swarm behaviors, and they shall be taken into account when the swarm actuation method is designed [51]. Another key issue that should be solved is the actuation and navigation of microrobotic swarms in 3-D environments, in order to guarantee the controllable mobility in in vivo environments. The influences of gravity forces on the generation and locomotion of swarms should be overcome. In addition, cytotoxicity of the microrobotic swarms is an important issue to be concerned. The materials with promising biocompatibility should be chosen [52] in order to reduce the cytotoxicity on normal cells. The swarms should also be biodegradable to weaken the negative effects on human health after accomplishing demanded tasks [53, 54].

The in vivo localization of microrobotic swarms through real-time imaging is critical for the implementation of precise feedback control. Although swarms have been navigated in vivo with vision feedback [23, 55], the current imaging modalities, such as fluorescence imaging, photoacoustic imaging, MRI, US, and X-ray fluoroscopy, still have limitations. Specifically, the fluorescence imaging and photoacoustic imaging can only be used for swarm localization in shallow tissues [3]. When using MRI, image artifacts caused by magnetic materials have negative impacts on the accurate position tracking of swarms [56]. The imaging quality of US is influenced by unrelated objects in living bodies, such as bone and air pockets [57]. The X-ray fluoroscopy is hazardous for living bodies under long-period observation [1]. Therefore, the spatiotemporal resolutions of imaging methods need to be enhanced. Combining multiple imaging modalities and integrating machine learning techniques could provide better imaging consequences.

The microrobotic swarms have also been exploited for environmental remediation and pollution control [58]. Compared to the conventional passive diffusion of solutes, the controllable swarms with locomotion capability bright more effective solutions to decontamination [59]. For instance, by triggering larger flow velocity and rotating fluid flow, magnetic biohybrid swarms can adsorb and remove heavy metal ions in contaminated water with enhanced efficiency [60]. Under rotating magnetic fields, organic pollutants were also degraded faster using helical swarms based on the increased interaction volume [61]. Although different swarms have been proposed for environmental protection, some important issues should be concerned. The swarms could also be sources of pollution by releasing organic molecules and inorganic ions into the environments [62]. The batch fabrication of agents can be hindered by complicated fabrication and post-processing procedures. Meanwhile, swarms should be equipped with recyclability to decrease the destructive impacts on the environment.

With the developments of multidisciplinary technologies, the magnetically driven microrobotic swarms have been promising platforms for biomedical applications. Efforts on material design, magnetic actuation methods, and control strategies are still required, in order to improve the controllability, reconfigurability, and function versatility of swarms. We envision that microrobotic swarms from labs are marching closer to practical applications.

Acknowledgements This work was supported in part by National Natural Science Foundation of China Project 62103347, Shenzhen Science and Technology Program (Grant No. RCBS20210609103155061), the start-up funding of CUHK-Shenzhen under Project UDF01001929, and the Shenzhen Institute of Artificial Intelligence and Robotics for Society under Project AC01202101109.

Declarations

Ethics Approval and Consent to Participate This article does not contain any studies with human or animal subjects performed by any of the authors.

Conflict of Interest The authors declare no competing interests.

References

Papers of particular interest, published recently, have been highlighted as:
• Of importance
•• Of major importance

1. Yang L, Yu J, Yang S, et al. A survey on swarm microrobotics. IEEE Trans Robot. 2021. https://doi.org/10.1109/TRO.2021.3111788.
2. Wang Q, Zhang L. External power-driven microrobotic swarm: From fundamental understanding to imaging-guided delivery. ACS Nano. 2021;15:149–74. https://doi.org/10.1021/acsnano.0c07753.
3. Chen H, Zhang H, Xu T, et al. An overview of micronanoswarms for biomedical applications. ACS Nano. 2021;15(10):15625–44. https://doi.org/10.1021/acsnano.1c07363.
4. Yu J, Wang Q, Li M, et al. Characterizing nanoparticle swarms with tuneable concentrations for enhanced imaging contrast. IEEE Robot Autom Lett. 2019;4:2942–9. https://doi.org/10.1109/LRA.2019.2924055.
5. Schuerle S, Soleiman, A.P, Yeh T, et al. Synthetic and living micropropellers for convection-enhanced nanoparticle transport. Sci Adv. 2019;5(4):eaav4803. https://doi.org/10.1126/sciadv.aav4803.
6. Li J, Esteban-Fernandez de Avila B, Gao W, et al. Micro/nanorobots for biomedicine: delivery, surgery, sensing, and

detoxification. Sci Robot. 2017;2:eaam6431. https://doi.org/10.1126/scirobotics.aam6431.

7. Kabir A, Inoue D, Kakugo A. Molecular swarm robots: recent progress and future challenges. Sci Technol Adv Mater. 2020;21:323–32. https://doi.org/10.1080/14686996.2020.1761761.
8. Park B, Zhuang J, Yasa O, et al. Multifunctional bacteria-driven microswimmers for targeted active drug delivery. ACS Nano. 2017;11:8910–23. https://doi.org/10.1021/acsnano.7b03207.
9. Yang Y, Liu J, Liang C, et al. Nanoscale metal-organic particles with rapid clearance for magnetic resonance imaging-guided photothermal therapy. ACS Nano. 2016;10:2774–81. https://doi.org/10.1021/acsnano.5b07882.
10. Wang Q, Yang L, Zhang L. Micromanipulation using reconfigurable self-assembled magnetic droplets with needle guidance. IEEE Trans Autom Sci Eng. 2021. https://doi.org/10.1109/TASE.2021.3062779.
11. Zhang H, Li Z, Gao C, et al. Dual-responsive biohybrid neutrobots for active target delivery. Sci. Robot. 2021, 6(52): eaaz9519. https://doi.org/10.1126/scirobotics.aaz9519.
12. Xie H, Fan X, Sun M, Lin Z, He Q, Sun L. Programmable generation and motion control of a snakelike magnetic microrobot swarm. IEEE-ASME Trans Mechatron. 2019;24:902–12. https://doi.org/10.1109/TMECH.2019.2910269.
13. Yang L, Yu J, Zhang, L. A mobile paramagnetic nanoparticle swarm with automatic shape deformation control. IEEE International Conference on Robotics and Automation. Paris, France, May 31-August 31, 2020. https://doi.org/10.1109/ICRA40945.2020.9197010.
14. Martel S, Felfoul O, Mathieu J, et al. MRI-based medical nanorobotic platform for the control of magnetic nanoparticles and flagellated bacteria for target interventions in human capillaries. Int J Robot Res. 2009;28:1169–82. https://doi.org/10.1177/0278364908104855.
15. Yan X, Zhou Q, Vincent M, et al. Multifunctional biohybrid magnetite microrobots for imaging-guided therapy. Sci. Robot. 2017, 2, eaaq1155. https://doi.org/10.1126/scirobotics.aaq1155.
16. Wang Q, Yang L, Yu J, et al. Real-time magnetic navigation of a rotating colloidal microswarm under ultrasound guidance. IEEE Trans Biomed Eng. 2020;67:3403–12. https://doi.org/10.1109/TBME.2020.2987045.
17. Zhou H, Mayorga-Martinez CC, Pané S, et al. Magnetically driven micro and nanorobots. Chem Rev. 2021;121(8):4999–5041. https://doi.org/10.1021/acs.chemrev.0c01234.
18.• Abbott J J, Diller E, Petruska A J. Magnetic methods in robotics. Annu Rev Control Robot Auton Syst, 2020, 3: 57–90. https://doi.org/10.1146/annurev-control-081219-082713. **This review provides a thorough introduction to the magnetic actuation methods for manipulating robotics remotely. Magnetic fields generated by magnetic materials and electromagnets, the magnetization of magnetic objects in an applied field, and applications of magnetic methods are discussed.**
19. Chen Y, Chen D, Liang S, et al. Recent advances in field-controlled micro-nano manipulations and micro-nano robots. Advanced Intelligent Systems, 2021: 2100116. https://doi.org/10.1002/aisy.202100116.
20. Schürle S, Kratochvil BE, Pané S, et al. Generating magnetic fields for controlling nanorobots in medical applications. Nanorobotics Springer. 2013. https://doi.org/10.1007/978-1-4614-2119-1_14.
21. Du X, Zhang M, Yu J, et al. Design and real-time optimization for a magnetic actuation system with enhanced flexibility. IEEE-ASME Trans Mechatron. 2020;26(3):1524–35. https://doi.org/10.1109/TMECH.2020.3023003.
22.• Wang Q, Chan K F, Schweizer K, et al. Ultrasound Doppler-guided real-time navigation of a magnetic microswarm for active endovascular delivery. Sci Adv. 2021;7(9): eabe5914. https://doi.org/10.1126/sciadv.abe5914. **Findings from this study suggest that magnetic microrobotic swarms can be navigated under ultrasound Doppler imaging guidance in vessels, and the upstream and downstream navigation of swarms are achieved.**
23. Manamanchaiyaporn L, Tang X, Zheng Y, Yan X. Molecular transport of a magnetic nanoparticle swarm towards thrombolytic therapy. IEEE Robot Autom Lett. 2021;6:5605–12. https://doi.org/10.1109/LRA.2021.3068978.
24. Dong X, Sitti M. Controlling two-dimensional collective formation and cooperative behavior of magnetic microrobot swarms. Int J Robot Res. 2020;39(5):617–38. https://doi.org/10.1177/0278364920903107.
25. Yang Z, Zhang L. Magnetic actuation systems for miniature robots: a review. Advanced Intelligent Systems. 2020;2(9):2000082. https://doi.org/10.1002/aisy.202000082.
26. Zeng L, Chen X, Du J, et al. Label-free separation of nanoscale particles by an ultrahigh gradient magnetic field in a microfluidic device. Nanoscale. 2021;13(7):4029–37. https://doi.org/10.1039/D0NR08383F.
27. Schaller V, Kräling U, Rusu C, et al. Motion of nanometer sized magnetic particles in a magnetic field gradient. J Appl Phys. 2008;104(9): 093918. https://doi.org/10.1063/1.3009686.
28. Hwang G, Paula A J, Hunter E E, et al. Catalytic antimicrobial robots for biofilm eradication. Sci. Robot. 2019, 4(29): eaaw2388. https://doi.org/10.1126/scirobotics.aaw2388.
29. De Lanauze D, Felfoul O, Turcot JP, et al. Three-dimensional remote aggregation and steering of magnetotactic bacteria microrobots for drug delivery applications. Int J Robot Res. 2014;33(3):359–74. https://doi.org/10.1177/0278364913500543.
30. Yan J, Bae SC, Granick S. Colloidal superstructures programmed into magnetic Janus particles. Adv Mater. 2015;27(5):874–9. https://doi.org/10.1002/adma.201403857.
31. Yu J, Yang L, Zhang L. Pattern generation and motion control of a vortex-like paramagnetic nanoparticle swarm. Int J Robot Res. 2018;37(8):912–30. https://doi.org/10.1177/0278364918784366.
32. Xie H, Sun M, Fan X, et al. Reconfigurable magnetic microrobot swarm: multimode transformation, locomotion, and manipulation. Sci Robot. 2019;4(28): eaav8006. https://doi.org/10.1126/scirobotics.aav8006.
33. Servant A, Qiu F, Mazza M, et al. Controlled in vivo swimming of a swarm of bacteria-like microrobotic flagella. Adv Mater. 2015;27(19):2981–8. https://doi.org/10.1002/adma.201404444.
34. Wang X, Hu C, Schurz L, et al. Surface-chemistry-mediated control of individual magnetic helical microswimmers in a swarm. ACS Nano. 2018;12(6):6210–7. https://doi.org/10.1021/acsnano.8b02907.
35. Vach P J, Walker D, Fischer P, et al. Pattern formation and collective effects in populations of magnetic microswimmers. J. Phys. D-Appl. Phys. 2017, 50(11): 11LT03. https://doi.org/10.1088/1361-6463/aa5d36.
36.•• Yu J, Yang L, Du X, et al. Adaptive pattern and motion control of magnetic microrobotic swarms. IEEE Trans Robot. 2021. https://doi.org/10.1109/TRO.2021.3130432. **This study provides an actuation method to trigger the generation of elliptical microrobotic swarms with motion dexterity and environmental adaptability. A control strategy is also proposed to automatically control the aspect ratio, long-axis orientation, and position of swarms.**
37. Yigit B, Alapan Y, Sitti M. Cohesive self-organization of mobile microrobotic swarms. Soft Matter. 2020;16(8):1996–2004. https://doi.org/10.1039/C9SM01284B.
38. Wang Q, Yang L, Wang B, et al. Collective behavior of reconfigurable magnetic droplets via dynamic self-assembly. ACS Appl

Mater Interfaces. 2018;11(1):1630–7. https://doi.org/10.1021/acsami.8b17402.
39. Snezhko A, Belkin M, Aranson IS, et al. Self-assembled magnetic surface swimmers. Phys Rev Lett. 2009;102(11): 118103. https://doi.org/10.1103/PhysRevLett.102.118103.
40. Snezhko A, Aranson IS. Magnetic manipulation of self-assembled colloidal asters. Nat Mater. 2011;10(9):698–703. https://doi.org/10.1038/nmat3083.
41. Yu J, Wang B, Du X, et al. Ultra-extensible ribbon-like magnetic microswarm. Nat Commun. 2018;9(1):1–9. https://doi.org/10.1038/s41467-018-05749-6.
42. Du X, Yu J, Jin D, et al. Independent pattern formation of nanorod and nanoparticle swarms under an oscillating field. ACS Nano. 2021;15(3):4429–39. https://doi.org/10.1021/acsnano.0c08284.
43. Massana-Cid H, Meng F, Matsunaga D, et al. Tunable self-healing of magnetically propelling colloidal carpets. Nat Commun. 2019;10(1):1–8. https://doi.org/10.1038/s41467-019-10255-4.
44. Wang Q, Yu J, Yuan K, et al. Disassembly and spreading of magnetic nanoparticle clusters on uneven surfaces. Appl Mater Today. 2020;18: 100489. https://doi.org/10.1016/j.apmt.2019.100489.
45. Jin D, Yuan K, Du X, et al. Domino reaction encoded heterogeneous colloidal microswarm with on-demand morphological adaptability. Adv Mater. 2021;33(37):2100070. https://doi.org/10.1002/adma.202100070.
46. Ji F, Jin D, Wang B, et al. Light-driven hovering of a magnetic microswarm in fluid. ACS Nano. 2020;14(6):6990–8. https://doi.org/10.1021/acsnano.0c01464.
47. Palacci J, Sacanna S, Steinberg AP, et al. Living crystals of light-activated colloidal surfers. Science. 2013;339(6122):936–40. https://doi.org/10.1126/science.1230020.
48. Ahmed D, Baasch T, Blondel N, et al. Neutrophil-inspired propulsion in a combined acoustic and magnetic field. Nat Commun. 2017;8(1):1–8. https://doi.org/10.1038/s41467-017-00845-5.
49. Li J, Li T, Xu T, et al. Magneto–acoustic hybrid nanomotor. Nano Lett. 2015;15(7):4814–21. https://doi.org/10.1021/acs.nanolett.5b01945.
50. Yang L, Yu J, Zhang L. Statistics-based automated control for a swarm of paramagnetic nanoparticles in 2-D space. IEEE Trans Robot. 2020;36:254–70. https://doi.org/10.1109/TRO.2019.2946724.
51. Wu Z, Chen Y, Mukasa D, et al. Medical micro/nanorobots in complex media. Chem Soc Rev. 2020;49:8088–112. https://doi.org/10.1039/D0CS00309C.
52. Goudu S, Yasa I, Hu X, et al. Biodegradable untethered magnetic hydrogel milli-grippers. Adv Funct Mater. 2020;30:2004975. https://doi.org/10.1002/adfm.202004975.
53. Avval M, Malekpour L, Raeisi F, et al. Introduction of magnetic and supermagnetic nanoparticles in new approach of targeting drug delivery and cancer therapy application. Drug Metab Rev. 2020;52:157–84. https://doi.org/10.1080/03602532.2019.1697282.
54. Siminzar P, Omidi Y, Golchin A, et al. Targeted delivery of doxorubicin by magnetic mesoporous silica nanoparticles armed with mucin-1 aptamer. J Drug Target. 2020;28:92–101. https://doi.org/10.1080/1061186X.2019.1616745.
55. Wrede P, Degtyaruk O, Kalva S, et al. Real-time 3D optoacoustic tracking of cell-sized magnetic microrobots circulating in the mouse brain vasculature. Sci Adv. 2022;8(19): eabm9132. https://doi.org/10.1126/sciadv.abm9132.
56. Zaitsev M, Maclaren J, Herbst M. Motion artifacts in MRI: a complex problem with many partial solutions. J Magn Reson Imaging. 2015;42(4):887–901. https://doi.org/10.1002/jmri.24850.
57. Sebeke L, Rademann P, Maul A, et al. Feasibility study of MR-guided pancreas ablation using high-intensity focused ultrasound in a healthy swine model. Int J Hyperthermia. 2020;37(1):786–98. https://doi.org/10.1080/02656736.2020.1782999.
58. Vaghasiya J, Mayorga-Martinez C, Matějková S, et al. Pick up and dispose of pollutants from water via temperature-responsive micellar copolymers on magnetite nanorobots. Nat Commun. 2022;13(1):1–10. https://doi.org/10.1038/s41467-022-28406-5.
59. Liu W, Chen X, Lu X, et al. From passive inorganic oxides to active matters of micro/nanomotors. Adv Funct Mater. 2020;30(39):2003195. https://doi.org/10.1002/adfm.202003195.
60. Zhang Y, Yan K, Ji F, et al. Enhanced removal of toxic heavy metals using swarming biohybrid adsorbents. Adv Funct Mater. 2018;28(52):1806340. https://doi.org/10.1002/adfm.201806340.
61. Mushtaq F, Chen X, Staufert S, et al. On-the-fly catalytic degradation of organic pollutants using magneto-photoresponsive bacteria-templated microcleaners. J Mater Chem A. 2019;7(43):24847–56. https://doi.org/10.1039/C9TA06290D.
62. Ying Y, Pumera M. Micro/nanomotors for water purification. Chem-Eur J. 2019;25(1):106–21. https://doi.org/10.1002/chem.201804189.