

An Overview of Micro/Nanorobot Swarm Control: From Fundamental Understanding to Autonomy

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Abstract—Micro/nanorobots have gained increasing attention worldwide owing to their promising potential in biomedicine. Benefiting from their small size and controllability, micro/nanorobots are ideal candidates for applications including targeted therapy, minimally invasive surgery, and drug delivery in physiological environments. However, the micro/nano-scale dimension hinders the ability and future application of miniature robots in the meantime. In recent years, swarm micro/nanorobotics has emerged as a rapidly developing interdisciplinary field. By simultaneously manipulating multiple micro/nanorobots, a micro/nanoswarm possesses larger delivery dose, better adaptivity to external environments, and better imaging contrast. Unlike macroscale robotic systems, implementing sensors or power supplies on micro/nanorobots is hard to achieve, which brings challenges for the control, feedback, and interagent communication of swarm micro/nanorobotics. In this review, we summarize state-of-the-art research about micro/nanoswarm, including actuation, imaging, and automatic control. Effective driving strategies and feedback methods provide the foundation for practical application. With the assistance of advanced

control algorithms, micro/nanoswarms are able to exhibit computational intelligence. Compared to manual control, micro/nanoswarm systems with high-level autonomy is able to conduct bio-tasks with better efficiency and precision. Moreover, the future challenges and directions for micro/nanoswarms are discussed. With this review, we aim to provide a comprehensive understanding and valuable guidance for swarm micro/nanorobotics researchers.

Index Terms—Automatic control, deep learning, medical imaging, micro/nanorobots, swarm micro/nanorobotics.

I. INTRODUCTION

MICRO/NANOROBOTS have drawn increasing attention in recent years owing to their promising potential in biomedical applications [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11]. As an interdisciplinary field, significant progress has been achieved in micro/nanorobotics due to the rapid development of materials, micro/nanotechnology, control engineering, biomedicine, and relative fields. Benefiting from the small size and active motion characteristic, researchers are making great efforts to utilize micro/nanorobots to address challenges currently facing conventional robotic systems, including targeted therapy [12], [13], [14], [15], [16], [17], [18], micro-manipulation [19], minimally invasive surgery [20], [21], [22], biosensing [23], [24], etc [25]. However, despite the superiorities of the small scale, it brings new issues. The capability of a single micro/nanorobot agent is highly restrained. Furthermore, tracking a micro/nano-scale target is demanding with medical imaging systems.

In nature, collective behaviors are common. Organisms tend to form groups for foraging, preying, and self-protection, such as ant colonies, bird flocks, and fish schools [26]. Inspired by this fundamental natural phenomenon, swarm robotics has revealed a prospective solution to enhance the application value of miniature robots [27], [28], [29]. A micro/nanoswarm is defined as multiple micro/nanorobots capable of performing swarm behaviors (e.g., locomotion, reconfiguration, and disassembly) under the balance between external stimuli and agent-agent interactions [30], [31]. Since a larger dose of microrobots is applied, not only is the delivery capacity of the swarm dramatically enhanced, but also a better imaging contrast is obtained. As for locomotion, micro/nanoswarms could provide some novel moving mechanisms for targeted navigation (e.g., asymmetric frictional force induced by a pitch angle [32]). Moreover, functionalization endows the microswarms with various additional properties, such as chemophoretic propulsion [33], phototherapy [34], photothermal therapy, and chemodynamic

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therapy [35]. Besides the above advantages, the major superiority of micro/nanoswarms is their reconfigurability. The swarm is a dynamically balanced collective. By tuning the parameters of the actuation field, the pattern of the swarm could be modulated accordingly, indicating strong robustness and adaptivity to various working environments [32], [36], [37], [38]. In comparison with conventional robotic systems, micro/nanorobots are limited by the tiny dimension and it is challenging to implement sensors, actuators, and power supplies on-board. Moreover, macroscale robot swarms normally rely on wireless communication to share position, velocity, and gesture information to perform collective behaviors [39], which is also impossible in micro/nano-scale. Researchers proposed to apply global external stimuli to trigger the formation and collective behaviors of micro/nanoswarms. Various power sources have been exploited to control the swarms, including magnetic field, light, acoustic field, and electric field. Both artificially fabricated microstructures and living microorganisms could serve as microrobot agents in the swarm. Synthetic microrobots could be specially designed with desired materials, structures, and functions according to working scenarios [40], [41]. Directly utilizing microorganisms exploits biological instincts for ideal control performance [42], [43], [44]. Other than controllable driving schemes, effective imaging methods are as important for practical bio-applications such as targeted delivery and treatment [45], [46]. In lab research, optical microscopies are widely utilized to monitor the swarms [47], [48], [49]. Strong contrast, high signal-to-noise ratio, and high spatiotemporal resolution make this method an ideal candidate for *in-vitro* studies. However, optical microscopies are not suitable for tracking swarms in opaque liquid solutions or closed physiological environments, which are common working scenarios in biomedicine. To facilitate the development of swarm robotics in practical applications, various established medical imaging modalities (e.g., ultrasound (US) [50], [51], [52], fluorescence imaging (FI) [23], [53], [54], positron emission tomography (PET) [45], [55]) have been introduced in micro/nanoswarm navigation for feedback. To date, most of the control and navigation tasks are finished manually. Researchers are involved in monitoring the swarm motion states via feedback images and adjusting the actuation field parameters. The efficiency and precision of such a human-in-the-loop (also referred to as open loop) control strategy highly rely on the experience and skills of the operator. An in-depth understanding of the swarm locomotion and formation mechanisms is required for better control performance. However, the concentration of the operators may decay during a long operation process, and some inappropriate inputs may even lead to the disintegration of swarms and the failure of tasks. To tackle this issue, the autonomy of swarm micro/nanorobotics is worth investigating. Impressive progress has been achieved in control theory these years, yet the controlled objects are mainly traditional systems such as motors [56] and drones [57], of which the fundamental mechanisms and models have been thoroughly studied. Micro/nanoswarms are underactuated systems, and various disturbances existing at micro/nano-scale make the swarm dynamics extremely complicated and almost impossible for modeling. All these factors indicate the automatic control of micro/nanoswarms is a significant challenge.

In this review, we summarize the recent development of swarm micro/nanorobotics. At first, various actuation methods for micro/nanoswarms are introduced. Corresponding pros and cons of these methods are compared. Then, medical imaging modalities applied to track swarms at both *in-vivo* and *in-vitro* scenarios are summarized. Subsequently, we review the studies focusing on the automatic control of swarms, including formation control, locomotion control, and pattern control. Eventually, the challenges micro/nanoswarms are facing presently in biomedicine applications and future prospects are discussed.

II. ACTUATION PRINCIPLES OF MICRO/NANOSWARMS

The actuation of a micro/nanoswarm refers to driving multiple micro/nanorobot agents to form a dynamically stable collective. Researchers have proposed to apply different power sources to provide global inputs and trigger the formation of micro/nanoswarms. Each method possesses unique suitable application scenarios, superiorities, and limitations. In this section, the basic mechanisms and characteristics of these actuation strategies are discussed. A brief summary is given in Fig. 1. Besides, microorganisms can also serve as microrobots to form swarms. Exploiting the instincts of these live matters could simplify the control process. Furthermore, some studies have reported that under the actuation of some specially designed or hybrid fields, micro/nanoswarms are able to perform 3-D behaviors against gravity.

A. Magnetic Actuation

Magnetic fields can provide an effective and highly controllable approach to drive magnetic micro/nanorobots. In low-strength and low-frequency situations, magnetic fields are harmless to human body and could penetrate into deep bio-tissues without significant decay [2], [58]. Furthermore, the fields in 3-D space could be precisely programmed and modulated if electromagnetic coils are applied to build the actuation system [59], [60]. In a broad sense, magnetic micro/nanoswarms can be categorized into magnetic force-induced swarms, torque-induced swarms, and weakly interacted swarms.

Magnetic gradient-induced swarms gather the micro/nanorobot agents mainly relying on the magnetic interaction. Magnetized matters tend to migrate to low-energy positions in the convergent fields, and dipole force takes dominance in the agent-agent interaction. The field utilized to drive this type of swarm should be stable and regular, too complicated variation is not required. Massana-Cid et al. applied paramagnetic colloidal microparticles in a rotating magnetic field. From a time-averaged aspect, the particles attract each other under the high-frequency field. Eventually, a carpet-like swarm is generated [61]. Dong et al. proposed to utilize 2-D permanent magnet arrays to build microrobot swarms [see Fig. 2(a)]. The magnet distributions are programmed according to desired potential energy maps and swarm patterns. The swarm is balanced between the external magnetic field and agent-agent repulsive forces [62]. Huang et al. presented to aggregate magnetic nanoparticles using a permanent magnet. The magnet is installed on a robotic arm to navigate the swarm for biofilm eradication [63].

Advantages				Limitations			
Magnetic field		Acoustic field		Magnetic field		Acoustic field	
Gradient force	Magnetic torque	Standing wave	Acoustic hologram	Gradient force	Magnetic torque	Standing wave	Acoustic hologram
- Concise formation and locomotion control - Stable swarm pattern - Good bio-compatibility - Safe to bio-tissues - Deep penetration depth	- Programmable fields - Reconfigurable swarms	- Controllable swarm pattern and motion - No limitation on the materials of swarm building blocks	Complicated swarm patterns can be obtained	- Limited swarm forms - Magnetic forces decay rapidly with distance - Magnetic building blocks are required	Swarms are vulnerable to disturbances	- Only symmetric patterns are available - Difficult to obtain diverse patterns and mobility simultaneously	- Hologram plates need to be specially designed - Swarms lack mobility and reconfigurability
Optical field		Electric field		Optical field		Electric field	
Photothermal	Photochemical	Dielectrophoretic force	Electrohydrodynamic flow	Photothermal	Photochemical	Dielectrophoretic force	Electrohydrodynamic flow
- High selectivity for swarm control - Concise motion control mechanism		- High controllability - Fast response		- Photothermal particles are required - Working environments are limited by the low penetration depth	- Photocatalytic particles are required - Swarms lack controllability	- Dielectric particles are required - Low bio-compatibility	

Fig. 1. Comparison between micro/nanoswarms actuated by various power sources, including the advantages and limitations of magnetic field, optical field, acoustic field, and electric field.

According to scaling law, torque actuation could be more efficient than force actuation in micro/nano-scale [71]. Under dynamic uniform magnetic fields, micro/nanorobots could form a stable pattern under dipole forces, fluidic interaction, and external fields. Yu et al. proposed that Fe_3O_4 nanoparticles tend to form chain-like structures when exposed to external fields. By applying oscillating fields and rotating fields, the nanoparticle chains will form ribbon-like swarms [32] [see Fig. 2(b)] and vortex-like swarms [72], respectively. After several years of research and development, these reconfigurable swarms have exhibited great application potential, such as micro-manipulation [73], targeted therapy [41], and thrombolysis [74]. Under an alternating field, aster-like swarms could be generated at the interface between two immiscible liquids. The swarm is governed by hydrodynamic streaming flows and chain-chain repulsive forces [48]. On liquid–air surfaces, the alternating field will produce snake-like swarms, formed because of the surface waves induced by particle collective behaviors [75]. Xie et al. focused on peanut-shaped magnetic microparticles. Under the actuation of different dynamic magnetic fields, the particles could trap each other using respective fluid fields and perform diverse swarm patterns (e.g., snake-like [76], liquid-like, vortex-like, ribbon-like, and chain-like [77]).

The aforementioned swarms possess strong interactions between internal agents (dipole forces and fluidic interaction). The swarm is weakly interacted if the interactions are weak enough to be negligible. In this scenario, the swarm behavior could also be regarded as consistent individual behaviors of a collective. Wu injected a group of helical-shaped microswimmers into a porcine eyeball. Under the control of a rotating magnetic field, the swimmers are able to propel themselves individually, penetrate the macromolecular matrix tissues inside the vitreous body, and reach the retina for targeted delivery [78]. Similarly, Yan et al. navigated the *S. platensis*-based microrobots in the

subcutaneous tissue, intraperitoneal cavity, and stomach of a mouse using a rotating permanent magnet for targeted cancer therapy [13]. Huang presented a planning scheme to navigate a microswarm in a vascular network, as shown in Fig. 2(c). The microrobots are driven by a uniform rolling field. With the guidance of the path planner, all the randomly dispersed robots will eventually reach the same target position passing through a maze-like environment [64]. Other than unified navigation, independent control is also of great research value. With heterogeneously designed microrobots, independent control of two groups of swimmers can be achieved. Wang [79] fabricated two types of magnetic helical swimmers with different surface properties. Under the actuation of rotating fields in two frequencies, a group of microswimmers can be navigated to two branches of a channel environment.

B. Light Actuation

Light-driven micro/nanorobots have been appealing recently given the maturity of laser-modulation technology [80]. Optical tweezer [81] and opto-mechanical control [82] have been widely applied for the manipulation of micro-devices and photosensitive soft robots. Especially, the high selectivity and directivity make light a powerful candidate for independent control of multiple microrobots [83], [84]. In terms of micro/nanoswarms, photothermal-based and photochemical-based methods are commonly utilized.

By applying photothermal micro/nanorobots, liquid medium, or substrate, the light can be converted to thermal energy. Local flows will be generated surrounding the microparticles owing to the temperature gradients induced by the laser radiation [65], [85], [86], [87]. Shi et al. [65] exploited the absorption rate difference of water and oil to light with specific wavelengths. Marangoni flow is created at the water/silicone oil interface

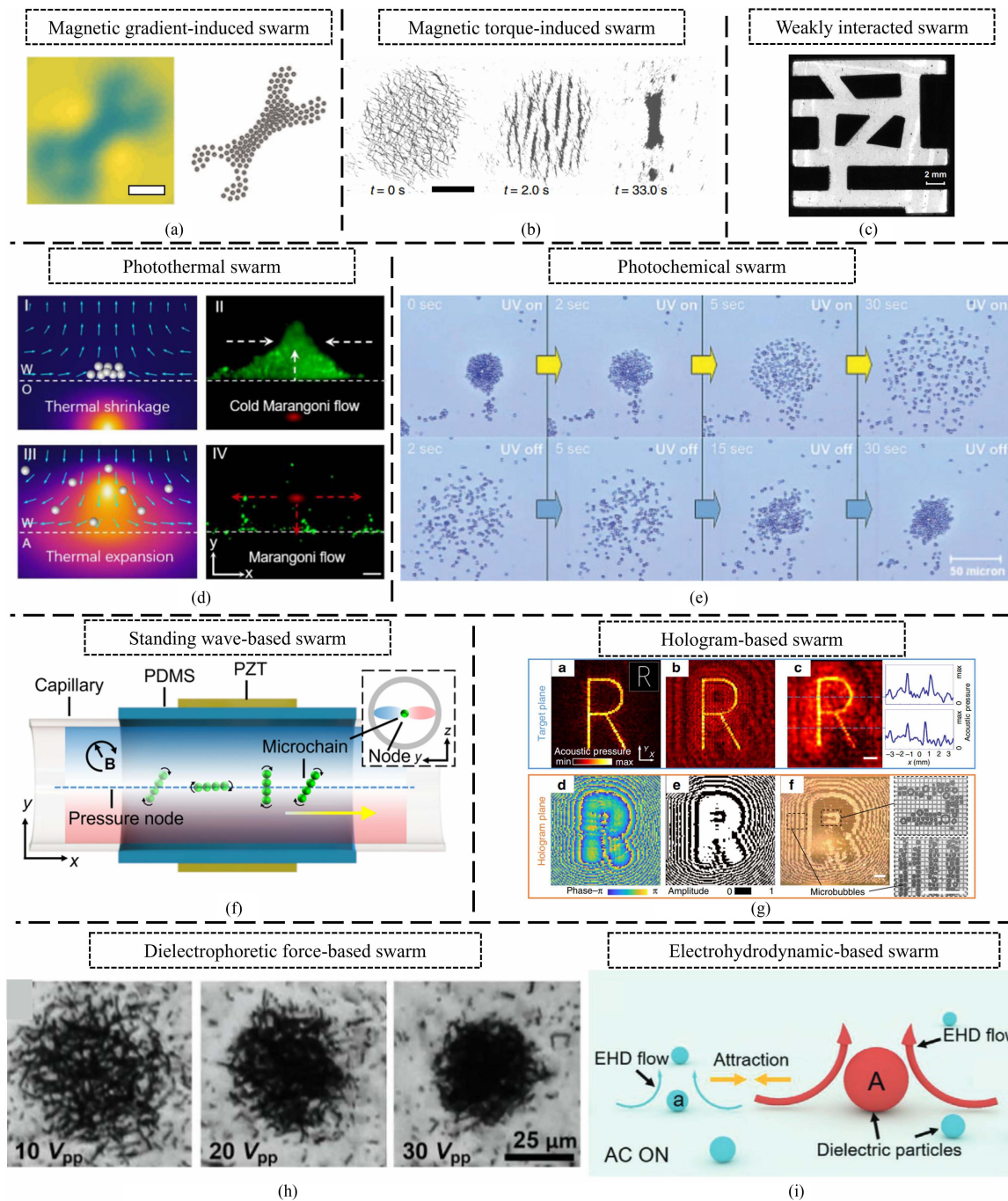


Fig. 2. Commonly applied power sources to actuate swarms. (a) Swarm actuated by a magnet array [62]. Scale bar: 5mm. (b) Ribbon-like swarm triggered by an oscillating field [32]. Scale bar: $800 \mu\text{m}$. (c) A weakly interacted swarm navigated in a maze [64]. (d) A photothermal swarm gathered by convection flow [65]. Scale bar: $10 \mu\text{m}$. (e) A photochemical swarm driven by UV [66]. (f) A swarm restrained by a virtual acoustic wall [67]. (g) Complicated pattern achieved by acoustic hologram [68]. Scale Bar: 1mm. (h) A swarm triggered by electric fields. The electric conductivity of the motors is enhanced by light [69]. (i) Illustration of electrohydrodynamic flows [70].

with the irradiation of a 1064 nm laser beam. Subsequently, the microparticles will migrate toward the irradiated area and form the swarm [see Fig. 2(d)]. This scheme is applicable to particles fabricated with various materials and even microorganisms. Lin et al. [88] proposed a general method to achieve the reversible assembly of a plasmonic microswarm.

Light radiation can also produce chemical gradients around the microrobots. The gradient will lead to the migration of microrobots, known as diffusiophoresis. Hong et al. [66] reported a type of photoactive $\text{SiO}_2\text{-TiO}_2$ Janus micromotor [see Fig. 2(e)]. Photons with enough energy could trigger the hole–electron separation of TiO_2 . Gathering and diffusion behaviors are observed

when ultraviolet (UV) light is switched OFF/ON. The TiO_2 will undergo both photocatalytic and nonphotocatalytic reactions. When the light is off, the particles will release OH^- and H^+ ions. The inward fluid induced by electrolyte diffusiophoresis will contract the swarm area. When the light is ON, the particles will generate O_2 . The resultant nonelectrolyte diffusiophoresis will then drive the particles to move outward [89]. Ibele et al. reported the schooling behaviors of AgCl particles in deionized water. The moving speed is up to $100 \mu\text{m/s}$ when exposed to UV light. The asymmetric photodecomposition can create electrolyte gradient surrounding the particles, and a gathering phenomenon will emerge after 1 min of UV illumination [90]. The chemical gradient can also be generated by the solution. Spiropyran will produce high concentration of merocyanine (MC) or MCH^+ with the illumination of UV spot, the induced convection will lead to the gathering, locomotion, and reconfiguration of silica microsphere swarms [91].

C. Acoustic Actuation

Acoustic waves have proven to be a safe and effective tool for wireless manipulation of tiny objects. In liquid or gas media, micro/nano-objects will be subjected to hydrodynamic forces (acoustic radiation forces) when exposed to acoustic fields.

Standing waves have been favored in acoustic propulsion research [92], [93]. When two acoustic waves with the same frequency, same amplitude, and opposite propagating directions interfere, multiple nodes, and antinodes will be generated. These modes are equilibrium positions. Solid particles tend to gather at the nodes or antinodes depending on the densities of particles and surrounding media [94]. Au–Pt nanomotors exhibit self-propulsion in hydrogen peroxide solution. When the US power is turned ON, the catalytic nanomotors will migrate toward the low-pressure node and generate a high-density pattern [95]. The assembly is reversible once the US field is cut off. As presented in Fig. 2(f), Zhang et al. proposed to build virtual walls using acoustic fields to confine the positions of nanoparticle chains [67]. The acoustic wave-triggered swarming has also been demonstrated using liquid metal colloidal. A dandelion-like is observed by applying a 730 kHz-US field. The swarm can be dispersed by reducing the frequency [96].

The major limitation of standing waves is that only symmetric pressure fields can be produced, resulting in symmetric swarm patterns. With a specially designed hologram plane, the phase distribution of a planar wavefront can be precisely modulated and accumulate particles to form desired patterns [68], [97], [98] [see Fig. 2(h)]. The distribution of the swarm can be systematically programmed, indicating a great application potential in microfabrication [99].

D. Electric Actuation

Polarized micro/nanorobots will undergo electrostatic forces from the external electric field and surrounding agents. Researchers have noticed that by exploiting these forces, dielectric micro/nano matter can exhibit swarm behaviors. The electric field is capable of transporting and assembling the entities with

prescribed trajectories and patterns [100]. Under the stimulation of alternating current (AC), Ti- and SiO_2 -covered silica microparticles are polarized. By tuning the frequency of the ac field, particles will gather in different states [101]. Diverse swarm organization can also be achieved using patterned electrodes, as reported by Albrecht et al. [102]. As for low-electric conductivity entities, researchers have applied laser exposure to assist the polarization and boost the electrostatic interaction [69] [see Fig. 2(h)].

The electric field accumulates charge near the electrodes owing to the ionic current. The arising convergent flows around the dielectric particles will then attract each other and form swarms [103], [104], [105]. Liang et al. applied microparticles with different sizes and dielectric properties to build self-organized hierarchical microswarms. The particles are gathered by the unbalanced electrohydrodynamic flows and then exhibit coordinated motion [70] [see Fig. 2(i)]. And during the locomotion, new particles will be continuously absorbed by the flow.

E. Actuation of Bio-Swarms

A bio-swarm refers to a collective constituted by hybrid biological robot agents. The biocompatibility and versatility make this type of swarm at the forefront of biomedicine research. As for swarms composed of living matters lacking mobility (e.g., stem cell spheres) [14], [106], the actuation mainly relies on the coating of magnetic particles, then the cell robots are able to respond to external magnetic fields as the robots introduced in Section II-A.

Microorganisms are potential candidates as bio-micro-robot agents. Exploiting the flagella structures and navigation organs, bacteria can provide highly efficient propulsion and steering mechanisms compared to manually designed micro-devices. Magnetotactic Bacteria (MTB) tend to align their moving direction to the external magnetic field owing to the magnetosomes embedded MTB cells. A gradient magnetic field is able to aggregate MTB at the convergent position [107] and precise motion control can be achieved by tuning the field direction [42]. The stable and controllable swarm behaviors indicate great potential for micromanipulation [108] and microassembly [43].

F. Actuation of Swarms in 3-D Space

Most of the studies in swarm micro/nanorobotics focus on 2-D planes. Substrates are utilized to hold the robot agents or provide necessary surface properties [109], [110]. Controllable 3-D motion of micro/nanoswarms has been challenging. In recent years, researchers have put much effort into investigating swarms' antigravity behaviors.

Simultaneously applying multiple power sources as actuation stimuli could exploit compound advantages [111]. Ji et al. presented a tornado-like microswarm under the actuation of a magnetic field and laser radiation [112]. The formation of the vortex-like swarm is triggered by the rotating magnetic field. With the illumination of near-infrared light, the convection fluid induced by the temperature gradient will lift the particles upwards. Similarly, Sun et al. utilize magnetic fluid and a high-frequency rotating field to form a steady disk-like swarm. When

the optical field is switched on, the swarm can be completely elevated and perform suspended motion [113].

3-D reconfigurable swarm pattern with a single control field has also been reported. Light radiation can produce convection flow and rotating vortices at the liquid–air interface. Frame-like 3-D structures are generated with this actuation scheme. The method applies to both nanoparticles and microorganisms [114]. Moreover, a spatial gradient magnetic field can form and navigate an MTB collective in 3-D space [107].

Another method to achieve 3-D swarm behaviors is to strengthen the interactions between swarm’s building agents. Magnetic nanoparticles tend to form a stable entity under the actuation of a dual-axis oscillating magnetic field. When increasing the pitch angle, the tilt angle of the swarm will increase accordingly [115], [116]. Ferrofluid droplets possess similar behaviors under a 300 Hz-rotating field. The solid-like ordering is observed and rolling motion is realized with a 90° pitch angle [117]. Moreover, a vertical oscillating field can trigger the split and self-assembly of ferrofluid droplets. A multilayer structure can be obtained eventually [118].

G. Typical Applications of Swarms

In previous sections we have introduced microswarms actuated by various power sources. Their unique advantages and limitations will lead to different application scenarios. Magnetic field-actuated swarms hold ideal controllability and bio-compatibility. With precise motion control and multiple form modes, magnetic swarms are excellent candidates for in-vitro studies (e.g., micro-manipulation [77] and circuit repairment [119]). As for in-vivo scenarios, researchers have proposed to apply surface processing to magnetize therapeutic microstructures [13], [14] or load drugs on magnetic microrobots to achieve targeted therapy [41]. Similarly, acoustic field is highly biocompatible, making it a powerful tool for biomedical applications. US-powered microrobots have been employed for intracellular targeted delivery [120], [121], [122]. Moreover, the positions and patterns of acoustic field-actuated microswarms can be modulated since the nodes of fields are reconfigurable. Thus, these agents are also suitable for lab research such as collective manipulation [95], [123]. Optical fields are most applied for in-vitro manipulation of microswarms [65], [66] since the penetration ability of light is relatively weak. Increasing the energy may even cause damage to bio-tissues. To address this issue, researchers utilized near-infrared rays to trigger photo-sensitive therapy using micromachines with specially designed structures and materials [34]. Owing to the highly restrained working environments, electric field-driven microswarms are less applied in biomedical scenarios. Researchers have presented pattern and motion control of microswarms using electric fields [101], [124].

III. IMAGING MODALITIES FOR MICRO/NANOSWARMS

An effective imaging method plays an important role for practical applications of micro/nanoswarms (e.g., bio-sensing [125], targeted therapy [74], drug delivery [45]). On the one hand, monitoring the real-time position is crucial for navigation tasks; on the other hand, the feedback images can reflect the state

information of micro/nanoswarms or surroundings. Depending on the working environments, swarm agent properties, and specific tasks, various imaging modalities have been implemented with the actuation systems of micro/nanoswarms [60], [126], [127], [128]. For in vitro scenarios, optical microscopes are widely applied. High contrast, high signal-to-noise ratio, high spatiotemporal resolution, and strong compatibility indicate this imaging method is extremely suitable for lab research [47], [76], [129]. However, during practical in vivo and *ex vivo* applications, or when swarms are immersed in untransparent bio-fluid, this vision-based scheme cannot be employed. To promote the development of swarm micro/nanorobotics in biomedicine, medical imaging strategies are introduced.

FI has been a powerful tool as a harmless imaging method for histological analysis and living cell examination. By utilizing self-fluorescence materials [13] or coating fluorescence probes [78], FI can also be employed to track active matters in physiological environments. Synthetic biomimetic helical swimmers functionalized with fluorophores are reported. Fluorescence signals can be clearly observed inside a porcine eye [78] and a mouse body [53]. Some natural organisms are intrinsically fluorescent. Drug loaded *Magnetococcus marinus* are applied for tumor clearance [130]. Similarly, *Spirulina* microalgae possess selective cytotoxicity to cancer cells. Yan et al. presented to utilize the microalgae-based microswimmers for cancer therapy. The swimmers are magnetized by Fe₃O₄ particles and exhibit robust controllability [13].

US is a well-established imaging technique that is widely used in clinical diagnostics. The reflected sound waves are able to image objects with Acoustic impedance differences. US could operate in two modes: B-mode and Doppler mode. The imaging depth of US can reach several centimeters. The real-time tracking experiments of micro/nanoswarms in a porcine eye [131], a porcine bladder [132], and whole blood [74] have been conducted, indicating strong bio-compatibility. However, the signal-to-noise ratio of B-mode is relatively low, and the imaging quality is vulnerable to disturbances. In contrast, Doppler mode measures the frequency shifts of the reflected waves, which contain velocity information of the observed objects. Since a swarm is a dynamic collective, Doppler mode imaging possesses robust performance in tracking micro/nanoswarms. Wang et al. present the usage of Doppler mode imaging to localize nanoparticle swarms [46] and cell collectives [106] in blood flow. The local flow velocity differences induced by the rotating swarms are precisely captured.

Photoacoustic imaging (PAI) also relies on the US signal to reconstruct the detected environments. The acoustic signals of PAI are generated from the excitation of laser pulses. Recently, PAI has been applied to track micro/nanoswarms. Yu et al. present the PAI-based nanoparticle swarm state analysis. The particle densities at suspended, spread, and swarm conditions are provided by the feedback images using pixel colors [133]. As for in vivo tracking, a swarm of *S. platensis*-based microswimmers coated with Fe₃O₄ particles and PDA are navigated in the subcutaneous tissues of a mouse [134]. The 3-D tracking of microcapillary-sized micromotors in mouse vascular systems is also realized [135].

Radionuclide imaging (RI) is based on exogenous agents—radionuclides, offering high sensitivity and no penetration limitation. RI is categorized as positron emission tomography (PET) and single-photon emission computed tomography (SPECT). PET combined with computer tomography (PET-CT) tracking of nanomotors of swarms in a phantom and a mouse bladder is demonstrated [45], [55].

Magnetic resonance imaging (MRI) relies on the excitation and relaxation of Hydrogen atoms in bio-tissues. MRI delivers no ionizing radiation and is widely used in diagnostics. A swarm of bio-hybrid microswimmers are localized inside a mouse stomach. Since magnetic actuation and MRI are not compatible, the actuation and imaging are finished on a time-sharing basis [13]. Moreover, the tracking capacity of bacteria using MRI is analyzed by Martel et al. [107]. Another magnetic field-based imaging method is magnetic particle imaging (MPI). MPI detects the iron oxide particle tracers and is capable of reconstructing 3-D structures with a high temporal resolution. Bente et al. realized 3-D localization of a Fe_3O_4 nanoparticle cloud [139]. Besides providing 3-D position information of the paramagnetic tracers, MPI can also be utilized to excite the thermal effects of particles. A localized magnetic hyperthermia inside a mouse body is realized using MPI guidance [140].

Optical coherence tomography (OCT) is a noninvasive medical imaging technique emerged in the 1990s. Notwithstanding the imaging depth is relatively shallow (1cm), the high spatial resolution and good compatibility with magnetic actuation systems make OCT suitable for real-time guidance and manipulation tasks [126]. Wu [78] applied clinical OCT imaging to track a swarm of micropropellers at retina.

IV. CONTROL OF MICRO/NANOSWARMS

Previous sections introduce the commonly used actuation and imaging methods for micro/nanoswarms. To obtain precise and on-demand swarm behaviors from micro/nanorobots to undertake specific tasks, swarm control is crucial. In contrast to single micro/nanorobot agents, swarms are dynamic and reconfigurable entities. Complicated behaviors bring more variables to the controller. In general, the control of micro/nanorobots is categorized into three aspects: formation control, locomotion control, and transformation control. Also, since the swarms are mostly governed by global inputs, the investigation of independent control of multiple swarm groups should be paid effort.

A. Formation Control

Section II presents various power sources to actuate micro/nanoswarms. The fundamental mechanisms of the formation of swarms with stable patterns can be divided into two categories. The first one relies on external convergent fields to gather micro/nanorobots. For instance, photothermal-based swarms are activated by the convection flow induced by temperature differences [65], [87]; a permanent magnet can collect magnetite nanoparticles to minimum potential position via magnetic forces [62], [63]; in an acoustic field, particles will be pushed and restrained to the nodes or antinodes [67], [96] [see Fig. 3(a)]. As for the other type of swarms, the equilibrium is achieved

through agent-agent interactions. Light illumination triggers the chemical gradients around photosensitive particles. Subsequently, the local flows surrounding each micro/nanorobots will attract or repel each other inside the swarm [89], [91]. The nanoparticle chains under the actuation of dynamic magnetic fields can form ribbon-like [32] and vortex-like swarms [72] [depicted in Fig. 3(b)]. The interactions between chains contain fluidic interactions and dipole forces.

As for the weakly interacted swarms, the interactions between swarm building blocks are negligible, and no external fields can restrain the agent distribution. The individuals in the swarm exhibit consistent behaviors independently [78]. These swarms without stable patterns are vulnerable to external disturbances.

B. Locomotion Control of Micro/Nanoswarms

To perform delivery and therapy tasks, targeted navigation and controllable motion of micro/nanoswarms are valuable for research. The convergent field-based swarms accumulate building blocks via gradient forces. Thus, by changing the position of the minimum potential point, the swarms migrate accordingly. This principle has been applied to drive magnetic swarms [136], [141], [142] [see Fig. 3(c)], optical swarms [91], and acoustic swarms [123] [see Fig. 3(d)].

Directional motion can also be achieved via asymmetric boundary effects. Pitch angles are introduced to provide asymmetric friction as driving force for micro/nanoswarms on silicon substrates [32], [47], [72]. Bidirectional motion of microchains along virtual acoustic walls is realized by rotating magnetic fields. The deviation between the rotation center and the geometric center of a chain is induced by the acoustic radiation force. Subsequently, the chains generate net displacement [67]. Xu et al. developed a needle-like microswarm. The robots could locomote in axial, lateral, and rolling modes under corresponding fields [143].

The weakly interacted swarms possess identical moving mechanisms as the building blocks. A swarm of helical microswimmers or surface rollers can be directly derived using a global rotating field [78] or rolling field [64], [144], respectively.

C. Transformation Control of Micro/Nanoswarms

The agent distribution and pattern of a micro/nanoswarm are tunable by changing the parameters of the external actuation field. This reconfigurability offers swarms adaptivity to tortuous, confined, and narrow environments. Direct contact delivers passive deformation. When navigated to pass through thin channels, the swarm may shrink itself subject to the surrounding obstacles [62], [145], [146]. This method relies on the cohesion of the swarm, no additional control effort is required. However, the physical extrusion may lead to particle loss or even disassembly of the swarm. To cope with this issue, active transformation has been studied. The reconfiguration of gradient field-based swarms can be realized by programming the external field energy. Dong et al. [62] presented a 2-D magnetic microrobot collective. The actuation magnets are modular. By changing the magnet distribution, the collective exhibits various patterns. Zhou [123] modulated the aspect ratio of an acoustic swarm

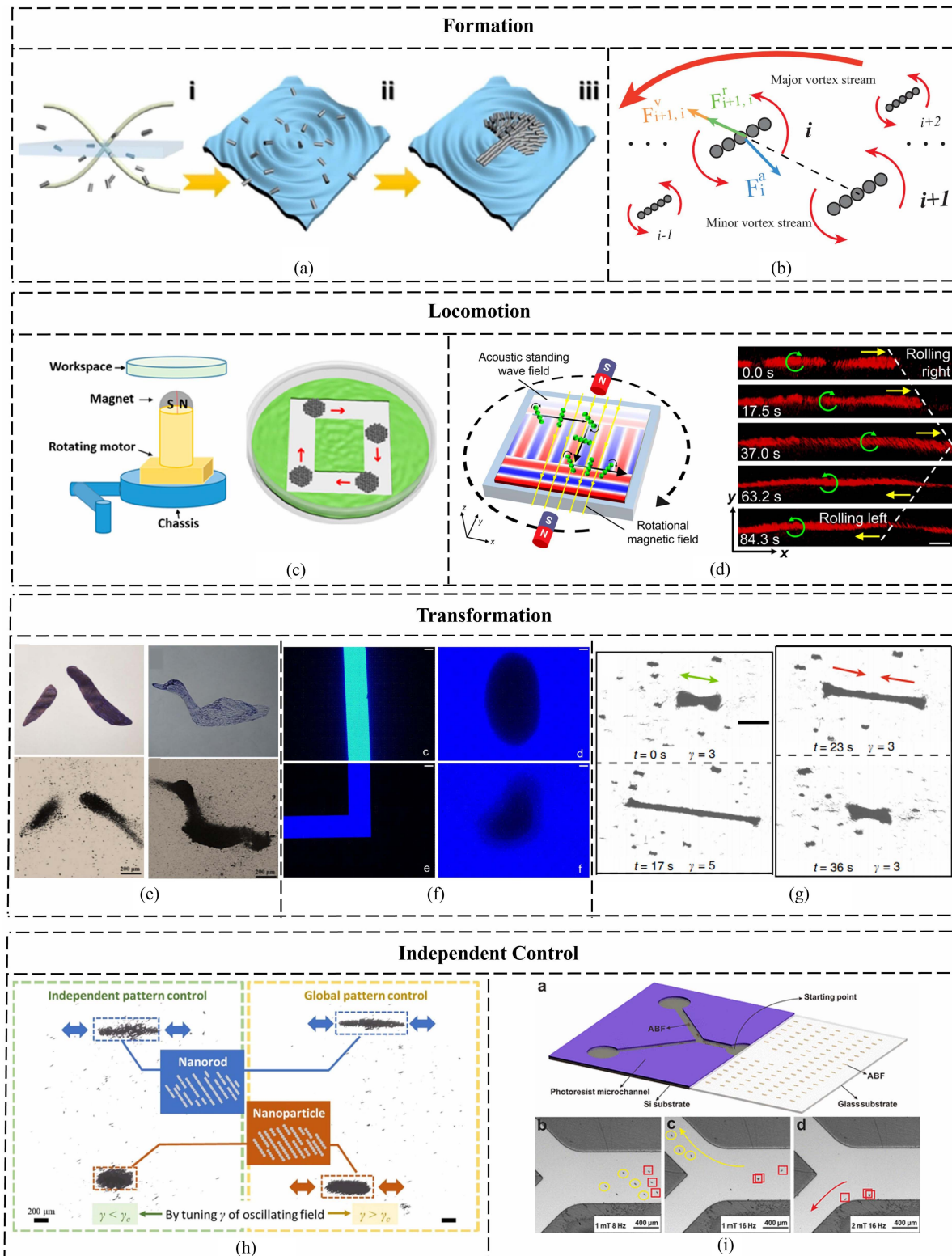


Fig. 3. Swarm behaviors and control. (a) A dandelion-shaped swarm triggered by standing waves [96]. (b) The interaction between nanoparticle chains inside a vortex-like swarm [73]. (c) A magnetic microswarm driven by a rotating permanent magnet [136]. (d) Swarms rolling along the virtual acoustic wall [67]. (e) Swarms with various patterns painted by a light spot [137]. (f) A line-shaped swarm and an "L"-shaped swarm. The pattern is controlled by changing the shape of light spots [91]. Scale Bar: 200 μm . (g) The elongation and shrinkage of a ribbon-like swarm [32]. Scale Bar: 800 μm . (h) The opposite deforming behaviors of a nanorod swarm and a nanoparticle swarm [138]. (i) Independent navigation of two groups of swimmers [79].

by adjusting the amplitude of the dual-frequency sinusoidal signal. Sun [137] painted figures with high resolution using photochemical micromotors. The light spot scans across the substrate and gathers particles, multiple complicated patterns including Chinese characters, a butterfly, and a swan are presented as shown in Fig. 3(e). A photochemical swarm has been reported to possess similar behavior. By applying different masks to modulate the shape of light spots, the silica particles form line-shaped and “L”-shaped swarms [91] [see Fig. 3(f)]. Xie et al. [77] achieved four forms of swarm morphologies by applying four different dynamic magnetic fields. Gardi et al. [147] reported a swarm consisting of micro-disks. Rotation, static, oscillating, and chain forms were presented under different dynamic magnetic fields. Moreover, the aspect ratios of ribbon-like [32] and vortex-like [72] magnetic nanoparticle swarms possess strong correlation with the ratio of actuation fields [see Fig. 3(g)], which provides insight into closed-loop control of swarm patterns [36].

D. Independent Control of Multiple Micro/Nanoswarms

The independent control at micro/nanoscale still remains a challenge. On the one hand, multiple micro/nano agents are mostly controlled via a global control input, and selective manipulation can be achieved only at some specific scenarios (e.g., light-actuated [156] and print circuit board-actuated microrobots [109]). On the other hand, the structures and moving mechanisms of micro/nano agents are limited by the sizes, indicating only a few degrees of freedom can be obtained. The key issue is to exploit the heterogeneity of the system, including the control field [157], [158], [159], microrobot agents [160], [161], [162], or boundary conditions [163]. In terms of swarm control, the same principle still applies.

The navigation of acoustic micro/nanoswarms is realized by the relocation of nodes. Zhou et al. [123] applied an acoustic tweezer to generate two local convergent fields to trap particles. According to the predefined trajectories, a sequence of convergent fields are activated in turn to guide the swarms. Consequently, the two swarms perform independent motion following the respective paths.

The usage of heterogeneous build blocks to form swarms for diverse control performance has also been studied. Du et al. present the different responses of nanoparticle swarms and nanorod swarms to the same oscillating field. The pattern change of the nanorod swarm experiences an anomalous stage and a normal stage as the field ratio increases, while the shape pattern of the nanoparticle swarm elongates monotonically [138] [see Fig. 3(h)]. Furthermore, the motion characteristics of the two swarms are also different. Researchers achieved to lead the swarms to two locations under the same actuation field by exploiting the velocity difference. The navigation in opposite directions is also realized on a tilted substrate [164]. Wang et al. fabricated hydrophilic and hydrophobic microswimmers which are geometrically and magnetically identical. The surface properties lead to distinct step-out frequencies of the two types of swimmers. In a vascular network environment, a group of swimmers are navigated to two different branches via selective control [79] [see Fig. 3(i)].

E. Automatic Control of Micro/Nanoswarms

To date, the operations of micro/nanoswarms are mainly finished by manual inputs, including formation, targeted navigation, and collision-free transformation. However, smooth control requires the operators to hold an in-depth understanding to the fundamental mechanisms of micro/nanoswarms; meanwhile, more variables are introduced in swarm control problems and simultaneously adjusting multiple parameters is demanding. The swarm building blocks bond with each other via dynamic interactions and field constraints. The inappropriate control inputs may break the stable states of swarms, or even cause the failure of navigation. To enhance the efficiency and accuracy of the swarm control performance, the autonomy of micro/nanoswarms should be investigated. The basic structure of a swarm controller is introduced in Fig. 5, and Table I summarizes the representative references.

The purpose of automatic formation control is to form a stable swarm pattern with a faster speed and make full use of the existing micro/nanorobot agents as much as possible. The convergent field-based swarms are able to gather building blocks autonomously owing to the feature of gradients [62], [65]. As regards the interaction-based swarms, different strategies are applied when building blocks are at different sizes. If the robot agents are at millimeter or micrometer scale, which are distinguishable to naked eyes or microscopic images, path planning algorithms are applicable to collect all the agents and form a swarm with high efficiency [76], [148]. Genetic algorithms are employed to plan the trapping orders of a snakelike microswarm and a ferrofluid droplet swarm [shown in Fig. 4(a)]. The time requirements to form swarms composed of various number agents can be reduced over 70% [148]. If the robot agents are at nanometer scale or even smaller, the individuals may be indistinguishable due to the limitation of the imaging tool. Meanwhile, the swarms will contain numerous robots, which makes it impossible to plan and trap every single agent in order. In this scenario, Yang et al. proposed a statistics-based algorithm to identify the swarm region. To gather more particles in the field of vision, the field frequency is tuned to modulate the swarm cover area [47] [see Fig. 4(b)].

Closed-loop motion control enables the precise locomotion of swarms to target positions. The complicated dynamics, fluid drags, and unknown disturbances introduce uncertainties to the control system. The snake-like swarm in [76] is navigated to follow a round reference path [see Fig. 4(c)]. Wang applied a magnetic tweezer to gather and navigate a swarm [149] [see Fig. 4(d)]. The swarm is driven by the convergent field generated by a mobile coil. A proportional-integral-derivative (PID) controller is designed to control the swarm position. Xu et al. applied a PI controller to drive the needle-like microswarm following an arbitrary path in three motion modes, the position errors were within 50 μm [143]. Yang formulated a linear quadratic integration (LQI) controller to govern the motion control of a nanoparticle swarm. The optimal scheme delivers a performance with better robustness and precision [47]. Motion control under the guidance of medical imaging strategies is reported by Wang et al. A US probe is applied to monitor the swarm position inside

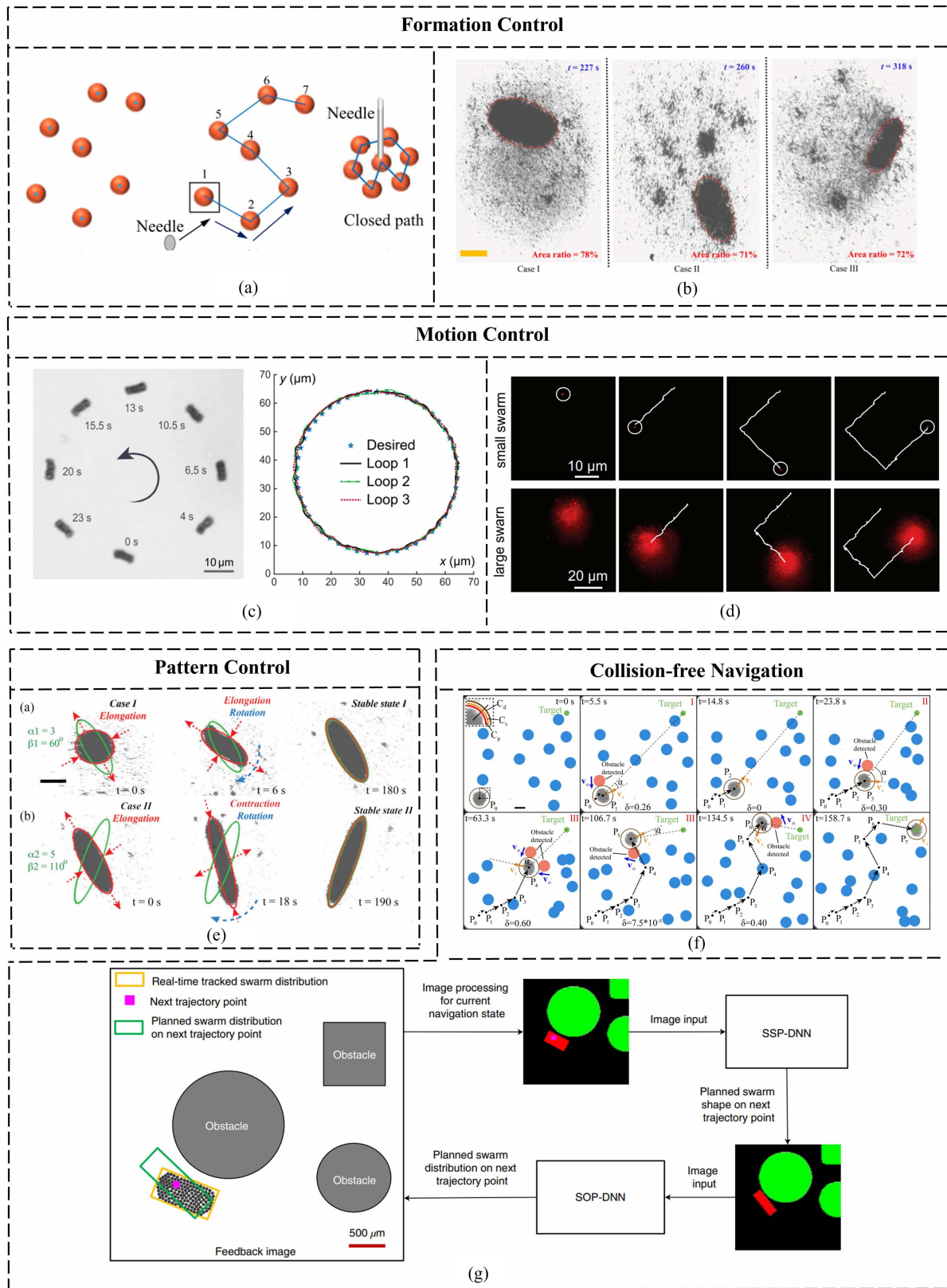


Fig. 4. Automatic control of swarms. (a) Genetic algorithm-based gathering strategy of a droplet swarm [148]. (b) Statistic-based algorithm to improve the gathering efficiency of nanoparticles [47]. Scale bar: 600 μm . (c) Motion control of a snake-like swarm along a round path [76]. (d) The closed-loop motion control with PID controller using a magnetic tweezer [149]. (e) Automatic pattern control of a vortex-like swarm with a fuzzy-logic controller [36]. Scale bar: 500 μm . (f) Automatic motion planning of a swarm in dynamic environments [153]. Scale bar: 500 μm . (g) Autonomous environment-adaptive navigation of a ribbon-like swarm [37].

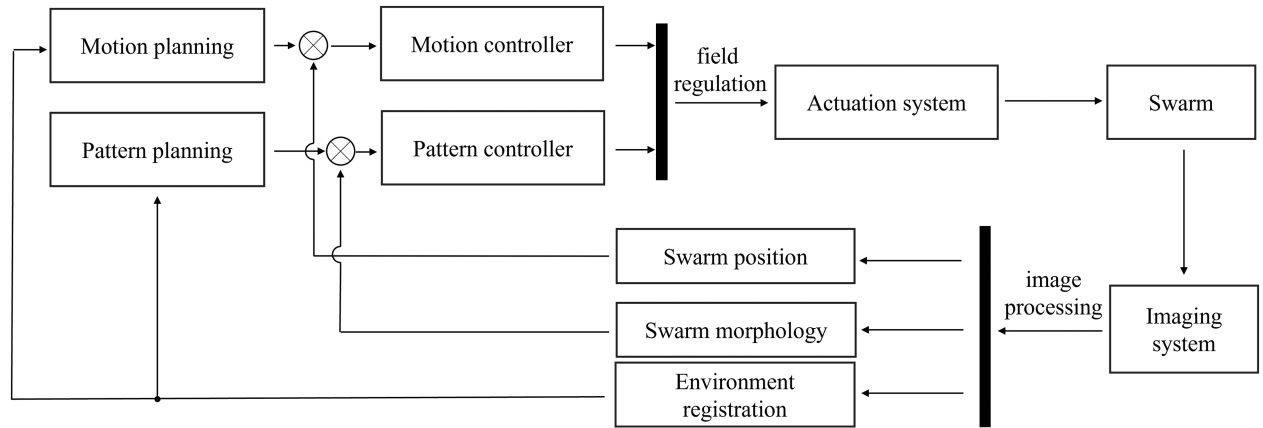


Fig. 5. Block diagram to illustrate the basic principles of automatic swarm control. Motion planning provides the trajectories or optimal moving directions. Pattern planning generates the reference swarm patterns according to the surrounding environments. The real-time position and morphology are obtained by processing the feedback images. The information of local environments is delivered to the planning modules. Two controllers are responsible for the motion and pattern control of the swarm, the calculated field parameters are delivered to the actuation system. Eventually, the swarm is controlled by the system as an end effector.

TABLE I
AUTOMATIC CONTROL OF MICRO/NANOSWARMS

Control Object	Category	Algorithm	References
Formation control	mm-scale building block	Genetic algorithm	[148]
	μ m-scale building block	Genetic algorithm	[76]
	nm-scale building block	Statistic-based algorithm	[47]
Locomotion control	Gradient force-based swarm	PID	[149]
	Interaction-based swarm	LQI	[148]
		SMC	[150]
		PID	[151]
Transformation control	Deforming control	Fuzzy-logic control	[36], [60]
	Swarm form switch	Finite state machine	[150]
Collision-free navigation	Off-line path planning	EB-RRT*	[152]
	On-line path planning	Hierarchical radar	[153]
		DQN	[154]
	Deforming control-included	Two-hierarchy neural network	[37]
		Shape reconfiguration planning	[155]

a chicken tissue-covered tank. The researcher utilizes frame difference to eliminate imaging noises and locate the swarm. The swarm precisely follows the given trajectory under the control of a PID controller [151].

Automatic pattern control has been a challenge when exploring the autonomy of micro/nanoswarms. First, the dynamics of deforming process are complicated and difficult to model. Second, the swarm patterns are vulnerable to external disturbances. Inspired by modern control theory, researchers introduce fuzzy-logic control to address this issue [36], [60]. The controller contains a feedforward input, an adaptive PID controller, and a fuzzy-logic control for parameter tuning. The current swarm patterns, deforming speed, and tracking closeness are considered to build the fuzzy knowledge base. Compared to conventional PID controller, the proposed method is capable of guaranteeing a fast and stable control performance [see Fig. 4(e)]. According to experimental results, this strategy applies to both ribbon-like and vortex-like swarms. Jiang et al. proposed a finite state machine and achieved the automatic switch of two swarm forms. The fluid field of each form is exploited to trap and release micro-objects for precise micro-manipulation [150]. The motion control is governed by sliding mode control (SMC).

Collision-free navigation is the key feature of applications including targeted therapy and delivery. With the assistance of path-planning algorithms, this problem has been thoroughly studied for single micro/nanorobots. In terms of swarm micro/nanorobots, some key points should be taken into consideration. The physical dimension and gesture of a swarm are not negligible during navigation, the planning algorithms should be modified to avoid the contact between obstacles and swarm boundary. Also, how to exploit the reconfigurability of a swarm to enhance its adaptivity to surrounding environments still lacks systematic solutions. Zhou et al. designed a dynamic planning strategy for a ribbon-like swarm to chase a dynamic target [152]. The collision is avoided by adding buffer layers to obstacle boundaries. The realize the dynamic chasing, an enhanced bidirectional rapidly exploring random tree star algorithm (EB-RRT*) is formulated. However, the update frequency of the path is still low (1.7–2.4 Hz), hindered by the computational burden. On-line planning methods are proposed for more dynamic scenarios. Jiang et al. utilized reinforcement learning to plan the moving direction of a vortex-like swarm. The deep Q-learning network (DQN) model takes the microscopic images as input and is applicable to swarms with different sizes [154].

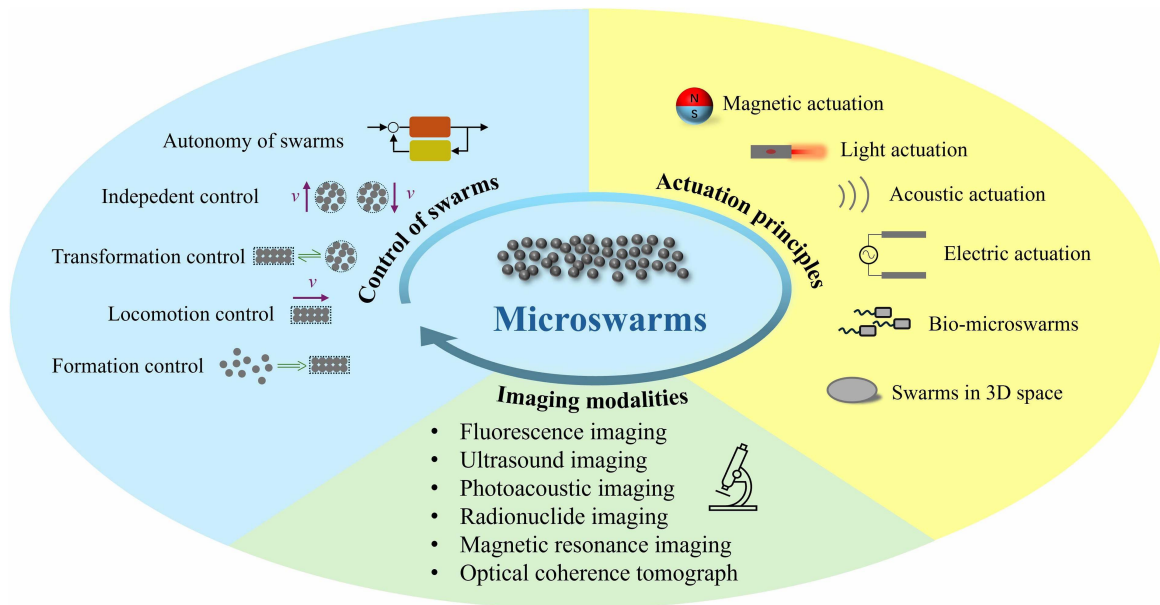


Fig. 6. Schematic illustration of the key features of swarm microrobotics. In section II, the main actuation principles of microswarms are introduced. Followed by the imaging modalities for feedback information. Then, the control schemes of microswarms are presented including the autonomy.

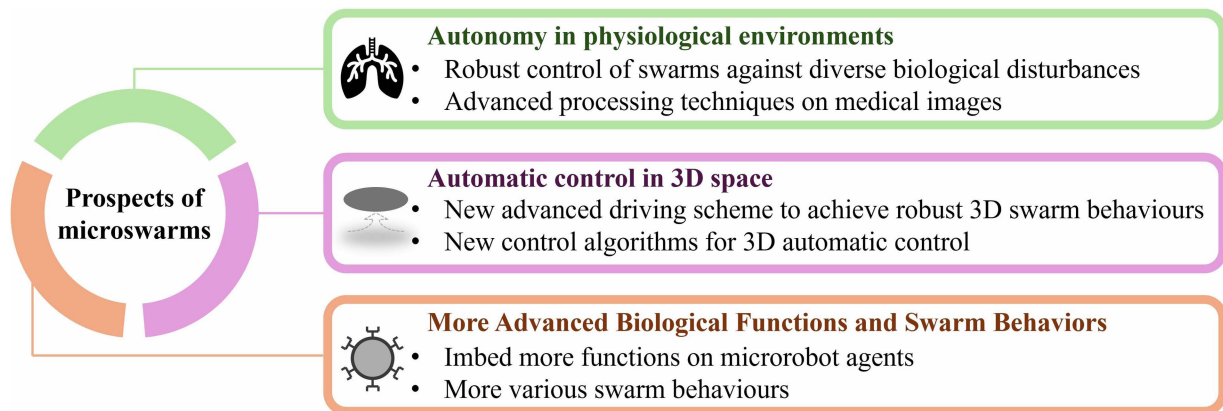


Fig. 7. Prospects of microswarms, including the autonomy of swarms in physiological environments for practical bio-applications, the automatic control in 3-D space for more complicated working environments, and more advanced functions and swarm behaviors for more working scenarios.

Liu et al. designed a hierarchical radar-based model and realized dynamic avoidance of multiple obstacles [153] [see Fig. 4(f)]. The above studies regard the swarms as rigid entities. Navigation of swarms capable of actively deforming has also been reported. Liu et al. utilized a wall detector and a PID pattern controller to realize self-elongation of a swarm to pass through thin channels [155]. Yang et al. proposed a deep-learning-assisted autonomous navigation scheme for microswarms. Along the predesigned trajectories, the scheme achieved real-time shape planning according to the local environments. The navigation in vascular-like networks indicates the algorithm is robust to various distributions of surrounding obstacles [37] [see Fig. 4(g)].

V. SUMMARY AND PROSPECT

Swarm micro/nanorobotics has provided a new direction to enhance the application value of micro/nanorobots in

biomedicine. The collective behaviors endow the micro/nano-scale active matter with better imaging contrast, larger loading capacity, and stronger adaptivity to undertake practical tasks such as delivery, therapy, and sensing. After decades of development, impressive progress has been achieved in this area. Various power sources are discovered to serve as actuation methods for micro/nanoswarms. Furthermore, the introduction of medical imaging modalities transfers the swarms from lab research to more practical environments (e.g., physiological environments). Depending on the robot materials, tasks, and working environments, these power sources and imaging methods possess unique advantages and limitations. The behaviors of micro/nanoswarms are analyzed. Understanding the basic mechanisms of these behaviors provides insight into control and autonomy. The advanced control algorithms and deep learning scheme grant micro/nanoswarms computational intelligence to perform high-level autonomy. In Fig. 6, we have

summarized the actuation principles, imaging modalities, and control strategies introduced in this review, to provide an intuitive and comprehensive guideline for researchers. It is predictable that swarm micro/nanorobotics will have a promising prospect. However, there are still several aspects remaining challenges (as shown in Fig. 7).

A. Autonomy in Physiological Environments

The current studies focusing on the autonomy of micro/nanoswarms are mostly still stuck in lab-research stage. The practical physiological environments are extremely unpredictable and numerous uncertainties exist. The flow of bio-fluids, surface mucus, and tissue peristalsis will all affect the behaviors and stability of swarms. Thus, more advanced control scheme is required to endow the swarms with adaptivity and robustness to complicated, and dynamic environments. Moreover, how to extract effective swarm information from medical images needs exploration. Not only positions, but morphological analysis is equally important in swarm control. The swarm area should be robustly and precisely identified in feedback images with low resolution, signal-to-noise ratio, and contrast.

B. Automatic Control in 3-D Space

The control and navigation of swarms on 2-D planes are strongly affected the surface properties of substrates. For complicated 3-D delivery tasks, automatic 3-D control of swarms is needed. To perform controllable 3-D motion, the swarm should be able to keep a stable pattern against gravity without physical support. The reported single field-actuated 3-D behaviors nowadays still haven't realized suspended motion control. The vertical gestures of the swarms indicate a new dimension for swarm research (e.g., new locomotion modes and more working environments). However, substrates are still necessary to hold the swarms. Genuine 3-D control has been reported by simultaneously using light and magnetic fields. Yet the introduction of multiple actuation fields will put more restrictions on the application scenarios.

C. More Advanced Biological Functions and Swarm Behaviors

The swarm behaviors are the foundations of the practical bio-tasks the swarms can undertake. For instance, thrombolysis is achieved via the fluid field surrounding the swarms, biosensing relies on the functionalization of micro/nanorobots, hyperthermia is attributed to the magnetocaloric effect, and the environment-adaptive navigation is enabled by the reconfiguration of swarms. To extend the application prospect of micro/nanoswarms, novel functions and swarm behaviors should be investigated. Since independent control for swarms composed of numerous micro-/nanoscale building blocks is still a major challenge, global input is the common choice to actuate and control swarms. How to achieve various swarm functions under this limitation should be tackled.

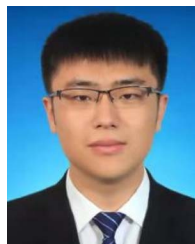
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