

Magnetic Microrobot Swarms for Navigating Intestinal Environments

Zihan Wang, Xinjian Fan, Zhan Yang, Xiangzhong Chen, and Sarthak Misra

Abstract—Microrobot swarms outperform individual agents in versatility and adaptability, yet their deployment in complex physiological environments *in vivo* remains challenging. Here, we propose a swarm reconfiguration strategy, which exploits two swarm configurations, namely circular and chain-like swarms, to navigate the gastrointestinal (GI) tract. The circular swarm navigates high-viscosity intestinal fluid, while the chain-like swarm traverses physical obstacles such as circular folds in the small intestine. A unified dynamic model is developed to predict both swarm configurations as solutions of the same force-equilibrium system under different external fields. We systematically evaluate the locomotion of the circular swarms in viscous mucus and the obstacle-traversal capability of the chain-like swarms. The reconfiguration and locomotion of microrobot swarms are further validated in a 3D-printed intestinal phantom, where the swarms traverse intestinal barriers, transition into a circular configuration for navigating mucus, and release cargo. The proposed swarm reconfiguration strategy holds promise for deploying microrobots toward targeted diagnosis and therapy in the GI tract.

I. INTRODUCTION

The emergent behavior of organisms is ubiquitous in nature, serving specific goals such as foraging, predation, and self-protection, as exemplified by ant colonies, bird flocks, and fish schools [1]. Inspired by such biological coordination, swarm robotics has emerged as a powerful paradigm for accomplishing complex tasks through the coordination of multiple agents. The versatility of this collective behavior manifests across a range of scales and application scenarios. For example, swarms of autonomous drones can detect and track targets across diverse environments [2], [3], while ground-based collaborative robots execute warehouse logistics and construction tasks [4]. This coordination paradigm has proven effective across diverse domains, establishing swarm robotics as a promising approach for multi-agent systems operating in complex and dynamic environments. Unlike their macroscale counterparts, microrobots hold promise for minimally invasive medical interventions, as they can access hard-to-reach regions within the human body [5]–[7]. Building on this inherent advantage, swarm-based coordination of microrobots further amplifies their clinical potential

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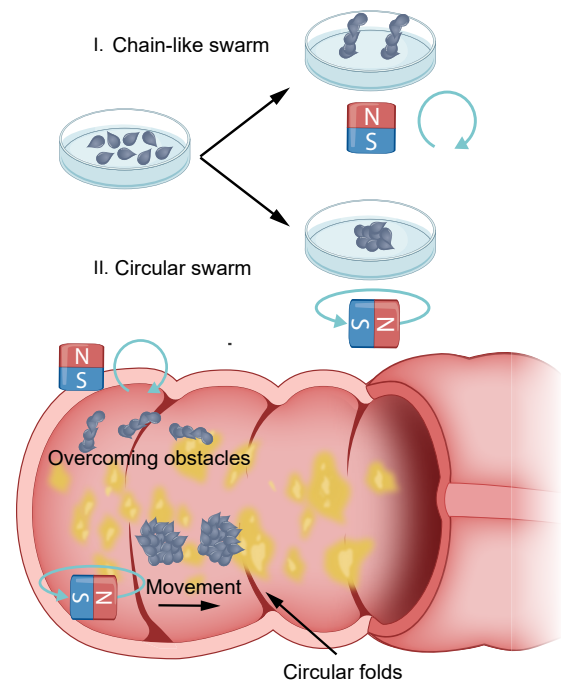


Fig. 1. The schematics show the formation of chain-like and circular swarms upon adjusting the orientation of external magnetic fields. The chain-like swarm is designed to overcome the circular folds and transform into a circular swarm to navigate the mucus.

through distributed sensing, cooperative manipulation, and robust operation that compensates for the limitations of individual agents.

Microrobots have demonstrated considerable promise in biomedical applications, including targeted drug delivery [8], [9], biofilm eradication [10], [11], and inflammatory bowel disease treatment [12], [13]. However, tasks of high complexity demand a level of intelligence beyond the capacity of a single microrobot, whose functionality is inherently constrained by its limited sensing, actuation, and payload. Swarm strategies provide a viable solution to addressing this limitation by coordinating multiple agents. The microrobot collectives can achieve emergent capabilities, such as environment-adaptive reconfiguration and cooperative force generation. Magnetic microrobot swarms have been extensively investigated with respect to their formation mechanisms [14], emergent patterns [15], [16], and biomedical applications [17], [18]. Under particle-particle interactions, microrobots can assemble into swarms exhibiting vortex, chain, or ribbon configurations [19]. Such swarms exhibit cooperative behaviors, such as fluid manipulation [20], cargo

transportation [21], and microsurgery [22]. The adaptability and versatility of microrobots have been markedly augmented by harnessing this swarm behavior. Although the collective behavior of magnetic microrobots has been demonstrated in idealized fluids, particularly regarding their dynamics and pattern formation, the feasibility of deploying such swarms in the complex physiological fluids and anatomical structures remains to be investigated.

Conventional treatment and diagnostics of intestinal diseases, such as oral drug administration and endoscopy, suffer from low site-specificity and limited access to the distal part of the small intestine, respectively. Magnetic microrobots offer a compelling approach for treating intestinal diseases owing to their precise targeting capability and high degree of controllability. Yet the intestinal environment poses two concurrent and physical barriers to the microrobot's navigation. First, the mucus layer lining the intestinal epithelium exhibits viscosities several orders of magnitude higher than water, severely impeding the propulsion of microrobots. Second, the circular folds, circumferential folds protruding into the intestinal lumen, constitute physical barriers that obstruct forward passage and cannot be overcome by the translational locomotion of magnetic microrobots. To tackle these challenges, we propose a swarm reconfiguration strategy for navigating the physiological fluids and anatomical structures in the small intestine. Two swarm configurations, a circular and chain-like swarm, are achieved by programming the external magnetic field. The circular swarm is designed for efficient locomotion through viscous mucus, while the chain-like swarm is capable of traversing high obstacles via a tumbling motion (see Fig. 1). The formation of these two configurations is investigated both theoretically and experimentally. A systematic parametric study of swarm formation is conducted by varying the field strength. The locomotion capabilities of the proposed swarms are validated in an intestinal phantom, and the cargo is released upon reaching the target site. This work demonstrates the navigation capability of microrobot swarms in intestinal environments, holding promise for targeted therapy of intestinal diseases *in vivo*.

II. METHODS AND CHARACTERIZATION

A. Fabrication of magnetic alginate microrobots

The magnetic alginate microrobots are fabricated using the centrifugally driven flow control, as detailed in our previous work [23]. Briefly, a polymer solution consisting of 4% w/v sodium alginate mixed with SmFeN powder at a weight ratio of 1:10 is loaded into a needle and ejected as a droplet by a centrifugal force, as shown in Fig. 2A. The ejected flows undergo instantaneous crosslinking upon contact with a Ca^{2+} solution. The interplay of centrifugal force, viscous drag, and surface tension governs the resulting teardrop morphology of the microrobots during the flow ejection.

B. Characterization on microrobots

The dimensions of the magnetic alginate microrobots are measured by optical microscopy. Using a relative centrifugal

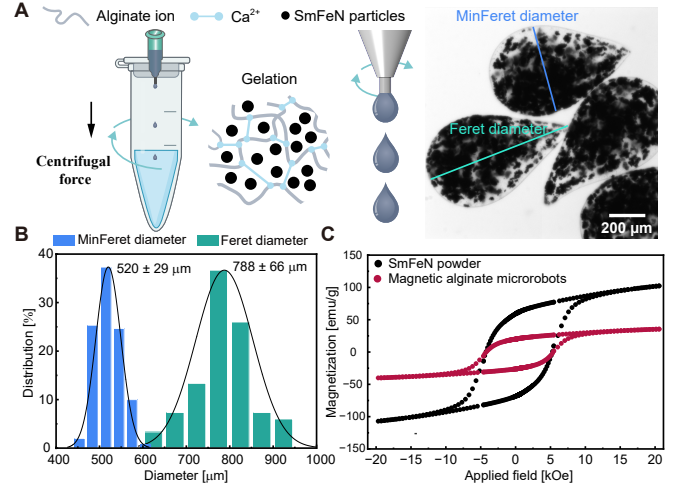


Fig. 2. Fabrication procedures and Characterization of magnetic alginate microrobots. (A) The fabrication procedures of the microrobots. (B) Frequency histograms show the Feret and MinFerret diameters of the microrobots. (C) The magnetization curves of SmFeN particles and magnetic alginate microrobots.

force of 68G, the microrobots are produced with an average Feret diameter of $788 \mu\text{m}$ and an average MinFerret diameter of $520 \mu\text{m}$, as shown in Fig. 2B. The incorporation of SmFeN powder enables the microrobot to move under external magnetic fields. Fig. 2C shows the measured magnetization of SmFeN powder and the magnetic alginate microrobot using a vibrating magnetometer. The saturation magnetization of SmFeN powder is around 104 emu/g, while the microrobot exhibits a saturation magnetization of approximately 37 emu/g. The measured parameters are subsequently incorporated into the dynamic model to investigate the hydrodynamic interaction among the microrobots.

C. Modeling

A cylindrical NdFeB permanent magnet is used for actuating the microrobot swarms. The field distribution of the magnet is governed by the constitutive relation between the magnetic flux density ($\mathbf{B}$) and magnetic field ($\mathbf{H}$), which is expressed as:

$$\mathbf{B} = \mu_0 \mu_{\text{rec}} \mathbf{H} + \mathbf{B}_r, \quad (1)$$

where μ_0 and μ_{rec} are the permeability of free space and recoil permeability of the magnet, respectively, and $\mathbf{B}_r$ is the remanent flux density of the magnet. Fig. 3A shows the calculated magnetic flux density of the magnet. The results show that the field strength decreases with increasing axial distance from the magnet. To validate the model, the magnetic flux density is measured at multiple points along the magnet axis. The quantitative agreement between the theoretical predictions and experimental measurements confirms the accuracy of the modeling.

In the presence of external magnetic fields, the magnetization of each microrobot aligns with the field direction under the applied magnetic torque. When microrobot i and microrobot j interact, microrobot i is subjected to a magnetic dipole-dipole interaction force ($\mathbf{F}_{i,j}^m$), a net gravitational force

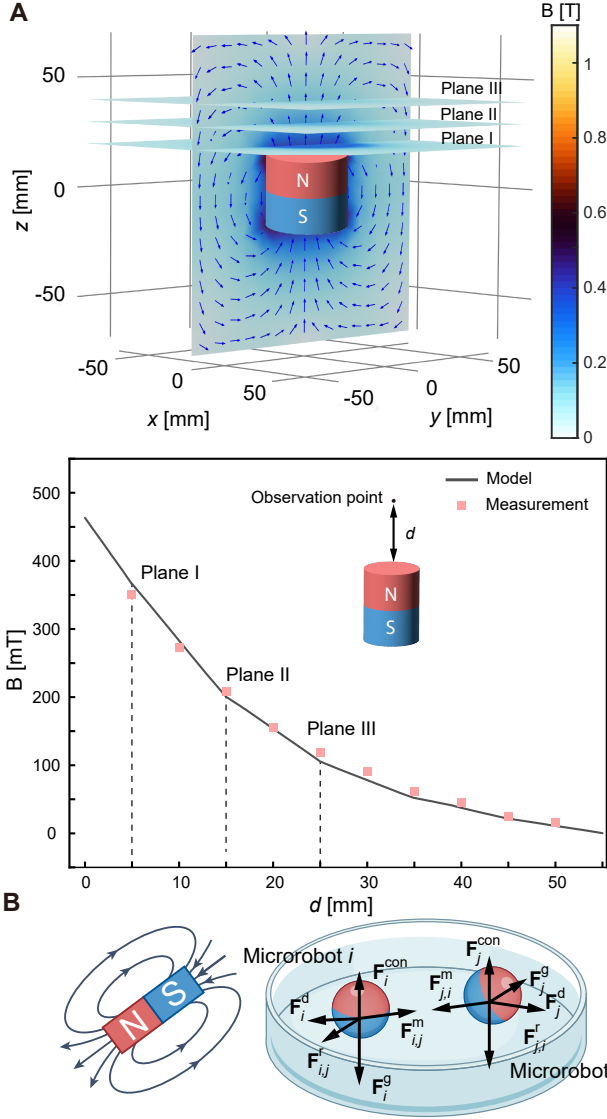


Fig. 3. Field distribution of a permanent magnet and the dynamic model of the microrobots. (A) Simulated field distribution of the permanent magnet. Comparison of the theoretical calculation and experimental data characterizing the magnetic flux density (B) distribution along the axial distance (d) from the magnet. (B) Force analysis of microrobots when exposed to the permanent magnet, including the magnetic dipole-dipole interaction force ($\mathbf{F}_{i,j}^m$), the net gravitational force ($\mathbf{F}_i^g$), the repulsive force ($\mathbf{F}_{i,j}^r$), the contact force ($\mathbf{F}_i^{\text{con}}$), and a viscous drag force ($\mathbf{F}_i^d$)

($\mathbf{F}_i^g$), a repulsive force ($\mathbf{F}_{i,j}^r$), a contact force ($\mathbf{F}_i^{\text{con}}$), and a viscous drag force ($\mathbf{F}_i^d$), as shown in Fig. 3B. In the low Reynolds number regime, inertial effects are negligible relative to the viscous drag, such that the microrobots maintain quasi-static force equilibrium throughout the locomotion. The force balance on the microrobot i is given by [24],

$$\sum_{i=1, j \neq i}^N \{ \mathbf{F}_{i,j}^m + \mathbf{F}_{i,j}^r \} + \mathbf{F}_i^{\text{con}} + \mathbf{F}_i^g + \mathbf{F}_i^d = 0, \quad (2)$$

where N is the number of the microrobots. When exposed to magnetic fields, each microrobot is magnetized and modeled as a magnetic dipole. The magnetic dipole-dipole interaction

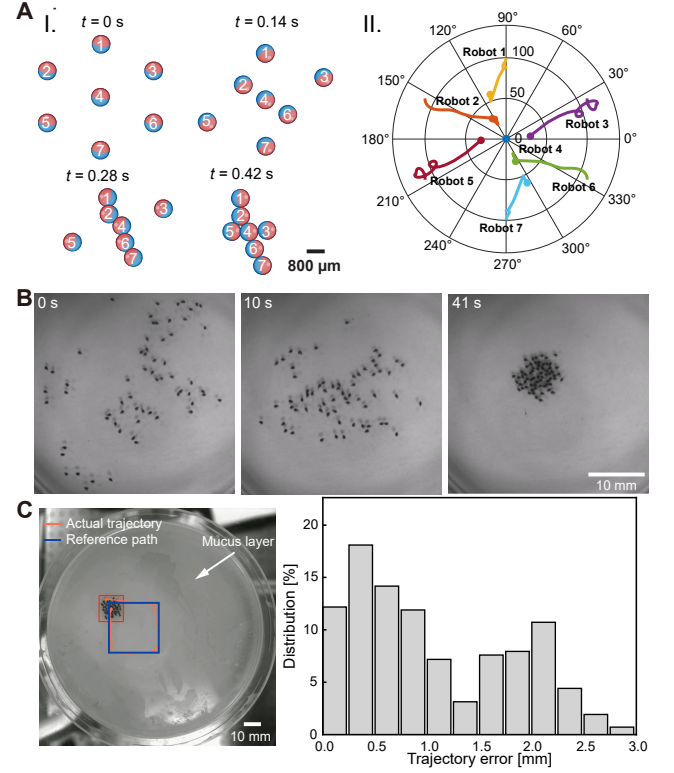


Fig. 4. The formation and the locomotion of the circular swarms. (A) Simulation results show the hydrodynamic interactions of seven microrobots under a rotating magnetic field, including (I) position changes and (II) trajectories of each microrobot. The radial axis represents their displacement in μm . (B) The formation of the circular swarm is experimentally observed under a permanent magnet with a rotating frequency of 5 Hz. (C) Snapshot of following a 2D square path and the trajectory error distribution. (See supplementary video)

between two microrobots can be evaluated as follows [25], [26]:

$$\mathbf{F}_{i,j} = \frac{3\mu_0}{4\pi r_{i,j}^5} [(\mathbf{m}_i \cdot \mathbf{r}_{i,j}) \mathbf{m}_j + (\mathbf{m}_j \cdot \mathbf{r}_{i,j}) \mathbf{m}_i + (\mathbf{m}_i \cdot \mathbf{m}_j) \mathbf{r}_{i,j} - 5 \frac{(\mathbf{m}_i \cdot \mathbf{r}_{i,j})(\mathbf{m}_j \cdot \mathbf{r}_{i,j})}{r_{i,j}^2} \mathbf{r}_{i,j}], \quad (3)$$

where $\mathbf{m}_i$ and $\mathbf{m}_j$ are the magnetic dipole moment of microrobots i and j , respectively. The vector $\mathbf{r}_{i,j}$ points from the microrobot i to the microrobot j . The net gravitational force ($\mathbf{F}_i^g$) is expressed as,

$$\mathbf{F}_i^g = (\rho_r - \rho_f) V_r \mathbf{g}, \quad (4)$$

where ρ_r and ρ_f are the densities of the microrobot and the surrounding fluids, respectively, and V_r is the volume of the microrobot, and $\mathbf{g}$ is the gravitational acceleration. When two microrobots come into contact with each other or with the boundary, the elastic forces ($\mathbf{F}_{i,j}^r$) and ($\mathbf{F}_i^{\text{con}}$) exist. These two forces are modeled as:

$$\mathbf{F}_{i,j}^r = K (r_{i,j} - 2r_i) \hat{\mathbf{r}}_{i,j}, \quad (5)$$

$$\mathbf{F}_i^{\text{con}} = -K (z_i - r_i) \hat{\mathbf{z}}, \quad (6)$$

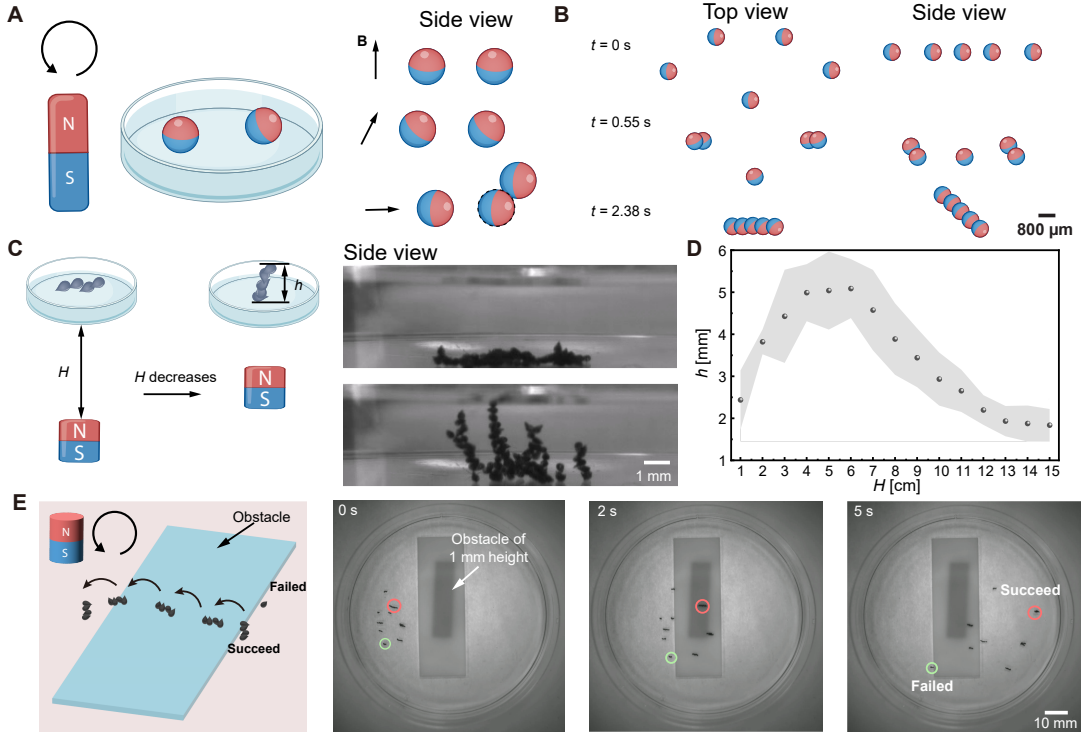


Fig. 5. The formation and characterization of the chain-like microrobot swarms. (A) Schematic illustrating the magnetic dipole-dipole interaction between two microrobots, resulting in the vertical elevation of the microrobot. (B) Simulation results show the position changes of five microrobots under a rotating magnetic field from top and side views. (C) The chain-like swarm forms as the magnet approaches the microrobots vertically, where the swarm height (h) varies with the working distance (H). (D) The changes in the height of the chain-like swarm versus the working distance. (E) The tall chain-like swarm traverses the obstacle with a height of 1 mm, while the short chain-like swarm fails to cross it. (See supplementary video)

where K is a stiffness coefficient of the microrobot, z_i is the distance from the centroid of the microrobot i to the boundary, r_i is the radius of the microrobot i , and the hat symbol represents the unit vector. On the basis of Stoke's law [19], the viscous drag force ($\mathbf{F}_i^d$) is given by

$$\mathbf{F}_i^d = -6\pi\eta r_i(\mathbf{v}_i - \mathbf{u}), \quad (7)$$

where $\mathbf{v}_i$ is the velocity of the microrobot i and $\mathbf{u}$ is the velocity of the surrounding fluid, and η is the dynamic viscosity of the fluid. This dynamic model could enable accurate prediction of their swarm behavior when microrobots are actuated by a magnet. In the following section, this model is solved to analyze the formation mechanisms of both circular and chain-like microrobot swarms.

III. EXPERIMENT RESULTS AND DISCUSSION

A. Formation and characterization of circular swarms

Microrobots aggregate into a circular swarm when subjected to a rotating magnetic field applied in the xy plane. Each microrobot operates below its step-out frequency, ensuring its magnetization aligns with the external field [27], [28]. The velocity of the individual microrobot is obtained by solving the dynamic model, from which the instantaneous position of every microrobot is updated at each time step. Fig. 4A-I describes the simulated dynamics of the microrobots initially dispersed at random positions at $t = 0$ s. When the rotating field is applied, each microrobot begins to rotate

synchronously with the field. Attractive magnetic dipole-dipole interactions arise between two microrobots when they are positioned at a certain orientation. This interaction drives the microrobots to approach one another. The simulated trajectories of all seven microrobots are depicted in Fig. 4A-II, where the displacement of each microrobot confirms their convergence. As the microrobots come into contact, the repulsive force activates and counteracts the attractive dipole-dipole interaction force. The interplay between these two forces drives the microrobots toward an equilibrium configuration. Additional microrobots are progressively included through the same equilibrium mechanism and self-organize into a stable circular swarm.

The experimental validation is conducted using a customized setup, in which the permanent magnet is mounted on a robotic arm and driven by a motor to generate a rotating magnetic field. The experimentally observed dynamics of microrobots are in good agreement with the simulation results, as shown in Fig. 4B. The microrobots aggregate into a circular swarm within approximately 41 s under the rotating magnetic field. The circular swarm morphology persists as long as the rotating field remains active. To evaluate the locomotion capability of the circular swarm, experiments are performed in a Petri dish containing a thin layer of mucus, mimicking the physiological environment of the GI tract [29]. By pre-programming the path of the robotic arm, the circular swarm is guided along a 30 mm square path,

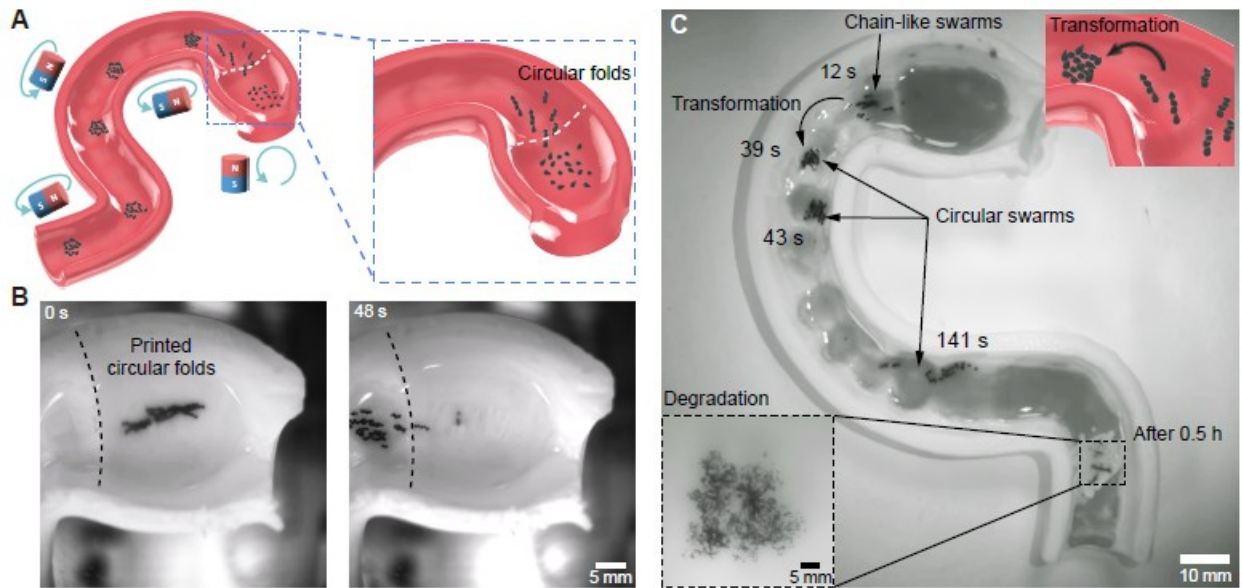


Fig. 6. Locomotion demonstration of the swarm in an intestinal phantom. (A) Schematic illustration of the swarm locomotion inside a phantom, where the permanent magnet is used for swarm navigation. (B) Experimental demonstration of obstacle crossing, where the microrobots assemble into chain-like swarms to successfully traverse the intestinal folds within 48 s. (C) Schematic and experimental demonstration of swarm transformation from chain-like to circular configuration, enabling their navigation in mucus. Time-lapse images show the sequential stages of transformation at 12 s, circular swarm at 39 to 141 s for locomotion, and subsequent degradation in physiological fluid for cargo release. (See supplementary video)

as shown in Fig. 4C. The swarm successfully follows the magnet while maintaining its circular morphology throughout locomotion. The trajectory error distribution confirms the motion control accuracy of the circular swarm in intestinal environments, with a mean trajectory error of 1.06 mm.

B. Formation and characterization of chain-like swarms

The chain-like swarm forms under a rotating field in the xz plane. When subjected to this field, one microrobot is driven to move horizontally toward the other microrobot. Upon contact, one microrobot is elevated by the z -component of the magnetic dipole-dipole interaction, inducing vertical chain assembly (see Fig. 5A). Additional microrobots are subsequently added to the chain ends through attractive dipole-dipole interaction, resulting in progressive chain elongation. The assembled chain-like swarm moves as a rigid body and exhibits tumbling motion, in which the chain periodically rotates about its long axis. Fig. 5B shows the simulated dynamics of five microrobots, demonstrating that a long chain forms through the sequential merging of shorter chains via the dipole-dipole attraction.

The influence of the working distance on the chain-like swarm morphology is further investigated experimentally. When the magnet is far from the microrobots, the weak field confines the microrobots to a flat and dispersed cluster on the substrate. As the working distance decreases, the chain-like structure tilts and elongates vertically, as shown in Fig. 5C. The height of the chain-like swarm is measured at different working distances, and the results are presented in Fig. 5D. As the working distance decreases, the increasing magnetic field strength enables more microrobots to be attracted into the vertical assembly, increasing the swarm height. The swarm height reaches a maximum of 5.09 mm at the working distance of 6 cm. However, as the distance decreases further, the magnetic gradient force exerts a

strong attractive force on the microrobots, pinning the swarm firmly on the substrate and suppressing further vertical chain elongation. This pinning effect not only limits the swarm height but also impedes the swarm's locomotion. Based on these results, a working distance of 4 to 6 cm is selected for subsequent experiments, as this range maximizes chain height while preserving sufficient locomotion capability. The chain configuration provides sufficient height for the swarm to overcome obstacles. The chain-like swarm successfully traverses a 1-mm-tall obstacle, as demonstrated in Fig. 5E.

C. Demonstration of microrobot swarms in an intestinal phantom

To evaluate the effectiveness of the microrobot swarms in a physiological environment, their locomotion is demonstrated in a 3D-printed intestinal phantom. The phantom includes a layer of mucus and a phosphate-buffered saline solution of pH 7.4 to simulate the rheological and chemical properties of the rabbit intestine. Fig. 6A illustrates two microrobot swarms sequentially navigating the intestinal phantom. In the first stage, the microrobots are assembled into a chain-like swarm to overcome the obstacles in the intestinal phantom, as shown in Fig. 6B. The vertically elongated chain configuration provides sufficient height to traverse this barrier. Then the swarm is transformed from a chain-like configuration to a circular configuration by modulating the rotating magnetic field from the xz plane to the xy plane. The circular swarm navigates through the viscous intestinal fluid under the magnetic gradient force, following the trajectory of the permanent magnet, as shown in Fig. 6C. Upon reaching the targeted site within the phantom, the microrobots spontaneously degrade and release their cargo, demonstrating the potential for targeted therapeutic delivery in the treatment of intestinal diseases. This demonstration validates the proposed swarm reconfiguration strategy, in

which the chain-like swarm enables obstacle traversal and the circular swarm facilitates navigation in the mucus, highlighting the versatility of the microrobot system in the GI tract.

IV. CONCLUSIONS

In conclusion, a swarm reconfiguration strategy that enables transformation between chain-like and circular configurations is developed to navigate the physiological fluids and anatomical structures in the small intestine. The circular swarm can navigate through GI mucus under the strong magnetic gradient, despite the high viscosity. This configuration effectively retains all microrobots within the swarm throughout the operation. The chain-like swarm exhibits a tumbling motion, and its elongated structure allows it to traverse physical barriers, making it suitable for navigation in the small intestine. Locomotion experiments in an intestinal phantom demonstrate the feasibility of the proposed swarm reconfiguration strategy, in which the microrobot swarm sequentially traverses intestinal obstacles in a chain-like configuration, transforms into a circular swarm for navigation in the viscous mucus, and achieves targeted cargo delivery. These results demonstrate an effective navigation strategy for microrobot swarms in the GI tract, opening new avenues for minimally invasive targeted therapy of intestinal diseases. Future work will focus on *in vivo* validation of swarm locomotion, the development of advanced control techniques, and targeted drug delivery in animal models.

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