

Topology and Coordination Govern Reconfigurable Multi-Module Robot Locomotion in Highly Viscous Environments

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Abstract—Microorganisms such as bundling bacteria and pairing spermatozoa exhibit sophisticated collective behaviors by coupling their flagellar dynamics through mechanical and hydrodynamic interactions. While these biological systems utilize reconfigurable topologies to optimize speed or stability, the influence of morphology-on-demand in synthetic modular swimmers remains poorly understood. Here, we investigate the locomotion of a reconfigurable, centimeter-scale modular robot operating in glycerin to emulate high viscosity swimming. Identical base modules reversibly assemble into configurations of $N = 1$ to 3 units via magnetic connections, each capable of switching between helical propulsion, analogous to bacterial flagellar bundling, and planar traveling-wave propulsion, analogous to synchronized sperm cells. A physics-informed model based on resistive-force theory and Stokes-flow mobility characterizes single-module propulsion as a function of flagellum geometry and actuation mode, providing a predictive baseline for the experimental investigation. Experiments in glycerin show that helical propulsion outperforms the planar gait by 40–60% under matched geometry, and that anterior puller-like actuation consistently exceeds posterior pusher-like actuation across all configurations. Role allocation (pusher or puller), rather than module count alone, governs collective speed: a triple face-to-face chain with one posterior pusher and two anterior pullers attains 1.81 ± 0.33 cm/s, a 78% improvement over a single module, while reversing the distribution reduces speed to 0.83 ± 0.19 cm/s. Turning experiments show that inter-module phase asymmetry is the primary driver of yaw, with anti-phase and mixed-phase configurations achieving peak turning rates of nearly $4.5^\circ/\text{s}$. These findings establish that reconfiguring topology and redistributing pusher-puller roles are essential design principles for modular swimmers in viscosity-dominated environments relevant to targeted drug delivery and non-invasive microsurgery.

I. INTRODUCTION

Locomotion at low Reynolds numbers ($Re \ll 1$) is governed by viscous forces that differ markedly from the inertial dynamics of larger organisms [1], [2]. In this regime, reciprocal motions (symmetrical ‘back-and-forth’ strokes) are rendered ineffective for propulsion, a constraint famously formalized by Purcell’s scallop theorem [1]. To achieve locomotion in low-Reynolds environments, microorganisms use non-reciprocal shape changes, primarily through rotating helical flagella or bending waves. Researchers have studied these methods extensively in bacteria [3], [4], sperm cells [5], [6], and other flagellated microorganisms [7], [8]. These findings have led to significant research on artificial microswimmers [9], [10].

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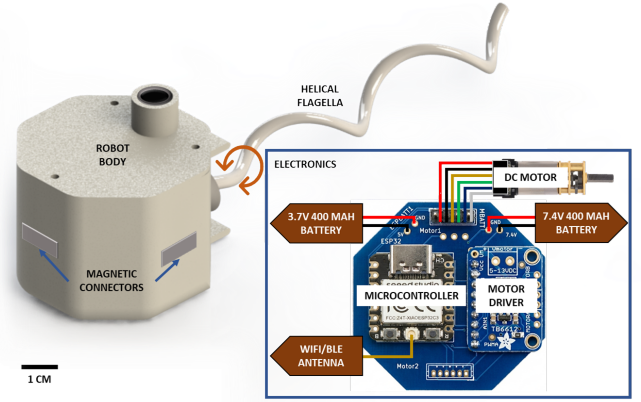


Fig. 1. **Overview of the reconfigurable modular swimming robot.** **Left:** Mechanical design of a single module showing the rigid body, magnetic side connectors for reversible assembly, and the helical flagellum driven by a rear-mounted DC motor. **Right:** Electronics architecture including the ESP32 microcontroller with integrated WiFi/BLE, motor driver (TB6612), and dual battery configuration (3.7 V logic supply and 7.4 V motor supply). The system enables speed control and wireless actuation of the flagellum.

Beyond individual propulsion methods, many microorganisms display collective behaviors that improve hydrodynamic performance. For instance, peritrichous bacteria bundle their helical flagella to boost thrust during movement [11], [12]. Sperm cells can synchronize their beating patterns or temporarily pair up to increase swimming efficiency in certain situations [13], [14]. These biological systems use mechanical coupling and hydrodynamic interactions to change their propulsion characteristics. Alterations in structure, whether through bundling, pairing, or clustering, affect drag distribution, force generation, and stability.

In synthetic systems, researchers have widely studied helical microswimmers powered by rotating magnetic fields [15], [16] and planar undulatory swimmers [17], [18]. However, these systems are almost exclusively studied as isolated, fixed-morphology units; the topology changes that give biological swimmers their adaptability, including bundling, pairing, and clustering, have no direct synthetic analog that has been systematically characterized. While individual helical swimmers have been well studied theoretically and experimentally, few investigations have examined how assembly topology, module count, and inter-module coordination jointly affect hydrodynamic performance [19]. Centimeter-scale platforms operating in high-viscosity fluids bridge this gap, reproducing viscosity-dominated dynamics while permitting controlled reconfiguration, direct optical tracking, and precise fabrication of inter-module connections

that remain inaccessible at the microscale [20], [21].

In this study, we address this gap using a reconfigurable modular swimming robot operating in glycerin ($Re < 1$). Identical centimeter-scale flagellated modules connect and disconnect via magnetic interfaces to form assemblies of $N = 1$ to 3 units, each capable of switching between helical and planar traveling-wave propulsion. By systematically varying assembly topology (face-to-face or side-by-side), module count, and actuation location (anterior or posterior), we quantify how morphology and coordination reshape the hydrodynamic force balance, forward speed, and turning maneuvers, providing a foundation for designing modular swimmers that can adapt their structure to task demands in viscous and confined environments relevant to targeted drug delivery and minimally invasive microsurgery.

This work makes three contributions. First, we present a centimeter-scale autonomous modular swimmer that mechanically switches between helical and planar traveling-wave propulsion within the same hardware design. Second, we present a physics-informed Stokes-flow model based on resistive-force theory [22] and the Rotne–Prager–Yamakawa (RPY) mobility tensors [23], which establishes a framework for describing the steady swimming speed as a function of flagellum geometry and actuation policy. Third, we provide a systematic experimental characterization of single- and multi-module configurations ($N = 1$ –3) in glycerin, revealing how topology, pusher–puller role allocation, and inter-module phase coordination jointly govern reconfigurable robot locomotion at low Reynolds number.

II. MATERIALS AND METHODS

A. Reconfigurable Low Reynolds Swimmer Platform

The reconfigurable swimmer platform includes identical centimeter-scale modules that work in a viscous Newtonian fluid, specifically glycerin, to mimic low-Reynolds-number conditions. Each module has a solid octagonal head and a replaceable flagellum (Fig. 1, SI Movie 00:05 - 00:11). The head provides structural support, houses embedded electronics and actuation components, and creates flat magnetic interfaces for reversible mechanical connection.

The head has a characteristic diameter of $D \approx 6.5$ cm, a height of 6 cm, and weighs 162 grams. An additional 130 grams of weight is added during experimentation to ensure the robot remains fully submerged, bringing the total weight to 292 grams. The helical flagellum is mounted coaxially to the posterior flat face of the head. Two flagellar lengths are investigated: a long configuration with total arc length $L = 15$ cm and a short configuration with $L = 8.5$ cm. For the helical configuration, the flagellum is fabricated as a rigid helix with radius $R_h = 1$ cm and axial wavelength (pitch) $\lambda = 6$ cm. The helix centerline is parameterized as

$$x = s, \quad y = R_h \cos\left(\frac{2\pi s}{\lambda}\right), \quad z = R_h \sin\left(\frac{2\pi s}{\lambda}\right), \quad (1)$$

where s denotes the arc-length coordinate along the helical axis. Rotation of the helix about its longitudinal axis generates propulsion through viscous drag anisotropy. The

robot’s parts were designed using SOLIDWORKS® and subsequently fabricated using Acrylonitrile Butadiene Styrene (ABS) material with a Bambu lab X1 Carbon® printer

To enable planar traveling-wave propulsion within the same geometric envelope, the helical backbone is mechanically constrained into a sheet-like configuration using evenly spaced transverse link elements distributed along its length, inspired by the design from previous studies [24], [25]. These links suppress out-of-plane deformation and enforce motion primarily within a single plane. Under rotation of the drive shaft, the constrained backbone produces an approximately planar sinusoidal waveform when viewed from the top. The resulting centerline can be approximated as

$$y = A \sin\left(\frac{2\pi x}{\lambda} - \omega t\right), \quad (2)$$

where $A \approx R_h$ corresponds to the effective wave amplitude and ω is the angular driving frequency. This design ensures that the two propulsion modes share comparable wavelengths and characteristic amplitudes, enabling direct comparison between helical and planar locomotion while isolating the influence of topology and coordination.

Reconfiguration is achieved through permanently embedded neodymium magnets located along selected flat faces of the head. The magnetic interfaces provide repeatable alignment and approximate rigid locking with minimal relative slip under hydrodynamic loading. This enables the assembly of formations with $N \in \{1, 2, 3\}$ modules. Two canonical dual-module topologies are investigated: (i) *face-to-face* coupling, where modules connect collinearly along their propulsion axes, and (ii) *side-by-side* coupling, where body axes remain parallel, and lateral separation is fixed by the magnetic interface. Larger assemblies extend the side-connected topology to form multi-module chains.

The complete set of morphological parameters (flagellum length, propulsion configuration, and actuation location) and assembly topologies (face and side connections) investigated in this study are summarized in Fig. 2. This design enables systematic examination of how geometric scaling, propulsion mode, and mechanical coupling jointly affect viscous force balance and translational performance.

B. Actuation and Control System

The electronic subsystem was designed to satisfy the functional requirements of the modular robot while maintaining a compact, waterproof design. The system enables precise control of propulsion speed and direction, provides live measurement of motor rotation, supports wireless communication for command and data transmission, and operates on battery power. All electronics are integrated into a single printed circuit board (PCB), designed in KiCad to fit within the sealed body cleanly. The PCB incorporates motor control, power regulation, and wireless communication, enabling speed regulation and consistent actuation. The electronic schematic and the corresponding PCB layout are shown in Fig. 1. Although the current implementation utilizes a single motor for actuation and propulsion, the PCB includes

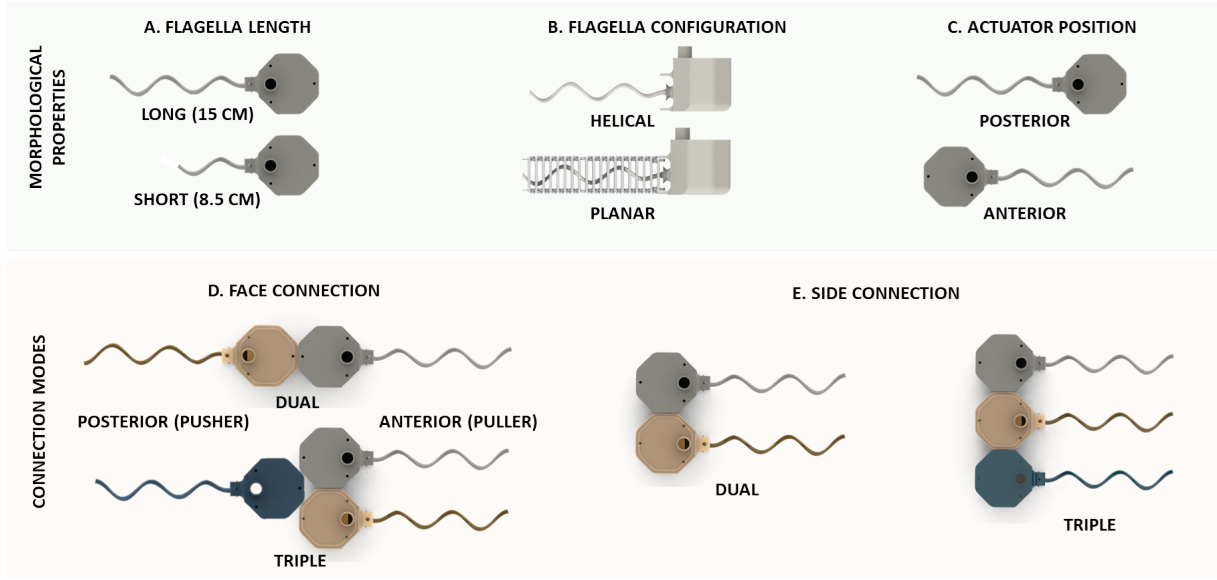


Fig. 2. **Design space of the reconfigurable modular swimmer.** Top row: Morphological parameters varied at the module level, including (A) flagellum length ($L = 15$ cm long and $L = 8.5$ cm short), (B) propulsion configuration (helical versus planar traveling-wave), and (C) actuator position relative to the body (posterior versus anterior). Bottom row: Assembly topologies enabled by magnetic inter-module connections, including (D) face-to-face coupling along the propulsion axis, shown for dual and triple assemblies with posterior (pusher) and anterior (puller) role assignments, and (E) side-by-side lateral coupling, shown for dual- and triple-module chains. Together, these morphological and topological parameters systematically alter body length, drag distribution, and hydrodynamic coupling, enabling controlled investigation of topology- and coordination-dependent propulsion under Stokes-flow conditions.

connections for a second motor and an auxiliary digital light sensor to support future design choices.

Each module integrates a 100:1 Pololu® Micro Metal Gearmotor (HPCB 6V) featuring an integrated 12 CPR quadrature encoder, a 100.37 : 1 gearbox, and a performance profile of 330 RPM with 1.6 kg·cm of stall torque. Actuation is managed by an Adafruit™ TB6612 1.2 A DC motor driver and a Seeed Studio® XIAO ESP32C3 microcontroller for closed-loop speed regulation. Each ESP32C3 module utilizes an external 2.4GHz antenna to improve BLE reliability. Power is provided by two lithium-polymer batteries: a 7.4 V 400 mAh pack for the motors and a 3.7 V 400 mAh pack for the logic circuitry.

Two actuation orientations are considered. In the *posterior propulsion* configuration, the flagellum is located at the rear of the module relative to the swimming direction (pusher-like). In the *anterior propulsion* configuration, the flagellum is positioned at the front (puller-like). By relocating the flagellum relative to the swimming direction, these configurations alter the module’s drag profile and the resulting hydrodynamic coupling within multi-module systems.

C. Experimental Setup

The experiments were conducted in a transparent acrylic tank (123 cm × 41 cm × 47 cm) sourced from CLEAR 2420 by Waterbox Aquariums®, filled with glycerin to a depth of 20 cm. LED strip lights were attached around the tank to illuminate the setup (Fig. 3). The working fluid was untreated laboratory-grade glycerin stored at room temperature. Prior to testing, the fluid was allowed to settle, and all experiments were performed at room temperature ($22 \pm 1^\circ\text{C}$). At this

temperature, glycerin has dynamic viscosity $\mu \approx 0.8\text{--}1.0$ Pa·s and density $\rho \approx 1250$ kg/m³.

The characteristic Reynolds number of the swimmer is estimated as

$$Re = \frac{\rho U L_c}{\mu}, \quad (3)$$

where U is the measured translational speed and L_c is the characteristic body diameter (≈ 0.06 m). For context, flagellated bacteria and spermatozoa operate at $Re \sim 10^{-4}\text{--}10^{-5}$ [3], [26]; our centimeter-scale platform operates at $Re \approx 0.4\text{--}0.8$ across the full tested frequency range (1.76–2.31 Hz). Although not strictly asymptotic Stokes flow, the dynamics are governed primarily by linear viscous drag, and the regime remains viscosity-dominated while being directly accessible to controlled experimental characterization.

D. Experimental Procedure

Each swimmer module was activated wirelessly using the onboard ESP32 microcontroller. Motor rotational frequency was set to 1.76 Hz and 2.31 Hz for an initial single-module frequency sweep, and standardized at 2.31 Hz for all subsequent multi-module, gait-comparison, and turning experiments (see Sec. III-B. Motor encoder feedback was used to maintain consistent rotational speed in all configurations and trials. No external flow or magnetic field was applied during the trials.

For each configuration (single module, face-to-face, side-by-side, and multi-side assemblies), the swimmer was manually positioned in the center of the tank and released from rest. To mitigate boundary effects, we maintained a minimum clearance of 10 cm from all tank walls and ensured an initial horizontal orientation for each trial. Data collection was

restricted to the tank's central volume to further minimize wall-induced hydrodynamic interference and boundary-layer interactions.

We performed synchronized dual-axis videography (top and side views) using a Logitech webcam sampling at 30 fps to record the swimmer's kinematics. Two reference sticks were placed in the tank to provide spatial scaling. The swimmer's center-of-mass position was extracted frame-by-frame using semi-automated tracking in MATLAB and the Tracker® software. Translational velocity was computed by differentiating the center-of-mass trajectory with respect to time. Each configuration was tested in at least three independent trials, and reported speeds correspond to the mean steady-state velocity after an initial transient of approximately 2 s.

To examine the influence of morphology and topology, experiments were conducted across three levels of complexity. At the single module level, we varied flagellum length (long $L = 15$ cm and short $L = 8.5$ cm, Fig. 2A), propulsion configuration (helical versus planar traveling-wave, Fig. 2B), and actuator position (anterior versus posterior, Fig. 2C). At the assembly level, we tested face-to-face dual and triple configurations with assigned pusher (posterior) and puller (anterior) roles (Fig. 2D), as well as side-connected dual and triple chains (Fig. 2E). Turning maneuvers were additionally characterized by prescribing asymmetric phase schedules across modules in both dual and triple assemblies. All experiments were conducted under identical fluid and actuation conditions at 2.31 Hz to isolate the effects of morphology, topology, and coordination on translational and rotational performance.

III. RESULTS

A. Low Reynolds Number Fluid Interaction Modeling

1) *Stokes-flow regime*: The swimmer operates in a viscosity-dominated regime ($Re < 1$), so inertial terms are negligible, and the surrounding flow is governed by the steady Stokes equations [1]:

$$-\nabla p + \mu \nabla^2 \mathbf{u} = \mathbf{0}, \quad (4)$$

$$\nabla \cdot \mathbf{u} = 0, \quad (5)$$

where $\mathbf{u}$ is fluid velocity, p is pressure, and μ is the dynamic viscosity of glycerin. In this regime, hydrodynamic force/torque depend linearly and instantaneously on translational and angular velocities; propulsion must therefore arise from non-reciprocal shape change or rotation with anisotropic drag.

2) *Flagellum drag model (RFT)*: Each flagellum is modeled as a slender filament of length L and effective radius a . Using resistive-force theory (RFT) [6], the local viscous force per unit length is

$$\mathbf{f}(s) = -(\xi_{\parallel} \mathbf{v}_{\parallel} + \xi_{\perp} \mathbf{v}_{\perp}), \quad (6)$$

where $\mathbf{v}_{\parallel} = (\mathbf{v} \cdot \mathbf{t})\mathbf{t}$ and $\mathbf{v}_{\perp} = \mathbf{v} - \mathbf{v}_{\parallel}$ are the parallel and perpendicular velocity components relative to the local tangent

$\mathbf{t}$. The drag coefficients satisfy $\xi_{\perp} > \xi_{\parallel}$; we use the standard slender-body approximations

$$\xi_{\perp} \approx \frac{2\pi\mu}{\ln(L/a)}, \quad \xi_{\parallel} \approx \frac{\pi\mu}{\ln(L/a)}. \quad (7)$$

3) Rigid rotating helix: geometry and resistance form:

For the helical mode, the centerline is parameterized by axial coordinate $x \in [0, L_x]$:

$$\mathbf{r}(x) = \begin{bmatrix} x \\ R_h \cos(2\pi x/\lambda) \\ R_h \sin(2\pi x/\lambda) \end{bmatrix}, \quad (8)$$

where R_h is helix radius and λ is the axial wavelength. The pitch angle ψ satisfies

$$\tan \psi = \frac{2\pi R_h}{\lambda}, \quad ds = \frac{dx}{\cos \psi}, \quad (9)$$

so the filament arclength is $L = L_x / \cos \psi$.

Let the swimmer translate with speed U along $+\mathbf{e}_x$ while the helix rotates about its axis with angular rate Ω_f . The resulting helical force and torque about the swimming axis satisfy the linear resistance relation [6], [27]:

$$\begin{bmatrix} F_x \\ T_x \end{bmatrix} = \begin{bmatrix} -A & B \\ B & -C \end{bmatrix} \begin{bmatrix} U \\ \Omega_f \end{bmatrix}, \quad (10)$$

with positive coefficients

$$A = L(\xi_{\perp} \sin^2 \psi + \xi_{\parallel} \cos^2 \psi), \quad (11)$$

$$B = L(\xi_{\perp} - \xi_{\parallel}) R_h \sin \psi \cos \psi, \quad (12)$$

$$C = L(\xi_{\perp} \cos^2 \psi + \xi_{\parallel} \sin^2 \psi) R_h^2. \quad (13)$$

The coupling term B is the source of propulsion: if $B = 0$ (no anisotropy or no helix), rotation cannot generate thrust.

4) *Force/torque-free swimming with body drag (closed form for U)*: Since the motor torque is internal, the net external hydrodynamic wrench (the combined 6D force and torque vector) acting on the complete swimmer is zero. This results in the balance equations $F_x + F_{\text{body}} = 0$ and $T_x + T_{\text{body}} = 0$, where F_x and T_x represent the propulsive thrust and torque generated by the flagellum.

We model the hydrodynamic drag on the robot's head along the swimming axis by defining translational and rotational resistances, ζ_t and ζ_r :

$$F_{\text{body}} = -\zeta_t U, \quad T_{\text{body}} = -\zeta_r \Omega_b, \quad (14)$$

where Ω_b is the body counter-rotation rate about the swimming axis $\mathbf{e}_x$. To account for the non-spherical (octagonal) shape of the robot's head, we expand these resistance coefficients using Stokes' drag law modified by empirical shape factors:

$$\zeta_t = C_t(6\pi\mu R_{\text{head}}), \quad \zeta_r = C_r(8\pi\mu R_{\text{head}}^3), \quad (15)$$

where R_{head} is the characteristic equivalent radius of the head, and C_t and C_r are dimensionless prefactors to account for the non-spherical geometry. With the relative motor driving rate Ω_m defined such that the flagellum's absolute

rotation is $\Omega_f = \Omega_b + \Omega_m$, solving the 2×2 balance yields the steady forward speed:

$$U = \frac{B\zeta_r}{(A + \zeta_r)(C + \zeta_r) - B^2} \Omega_m. \quad (16)$$

Equation (16) provides a direct mapping from flagellar geometry (L, R_h, λ), fluid viscosity (μ), head geometry (R_{head}, C_t, C_r), and actuation rate (Ω_m) to the predicted steady speed.

5) *Planar traveling-wave mode (matched wavelength):*

For the planar mode, the filament centerline is prescribed as a traveling wave in the x - y plane:

$$y(x, t) = A_{pw} \sin(2\pi x/\lambda - \omega t), \quad (17)$$

with wavelength λ chosen to match the helical mode. The local deformation velocity $\partial \mathbf{r}/\partial t$ is substituted into the same RFT law and integrated along the filament to obtain the net thrust; force/torque balance then yields the predicted U for the planar gait.

6) *Multi-module assemblies: compact mobility formulation:* When N modules dock magnetically and behave as a rigid assembly, the structure has a single global spatial velocity $\mathbf{V} = [\mathbf{U}; \Omega] \in \mathbb{R}^6$. We discretize all flagella (and body surfaces) into N_b hydrodynamic nodes at positions $\{x_i\}$. Stacking the node forces and velocities as $\mathbf{f} \in \mathbb{R}^{3N_b}$ and $\mathbf{v} \in \mathbb{R}^{3N_b}$, the Stokes mobility relation is:

$$\mathbf{v} = \mathbf{M}(\mathbf{q})\mathbf{f}, \quad (18)$$

where $\mathbf{q}$ is the spatial configuration vector of all nodes, and $\mathbf{M}(\mathbf{q})$ is the mobility matrix. To ensure physical validity and well-conditioned interactions even under close docking, $\mathbf{M}(\mathbf{q})$ is constructed using the Rotne-Prager-Yamakawa (RPY) tensor [23], [28]. Rigid-body kinematics impose:

$$\mathbf{v} = \mathbf{J}(\mathbf{q})\mathbf{V} + \mathbf{v}_{shape}, \quad (19)$$

where the Jacobian matrix $\mathbf{J}(\mathbf{q})$ maps the global assembly velocity $\mathbf{V}$ to the individual node velocities, and $\mathbf{v}_{shape}$ encodes the prescribed local deformation velocities (e.g., from helical rotation or planar traveling waves). Enforcing the force- and torque-free swimming condition gives $\mathbf{J}^T \mathbf{f} = \mathbf{0}$. Eliminating $\mathbf{f}$ by inverting the mobility matrix into a resistance matrix ($\mathbf{R} = \mathbf{M}^{-1}$) yields the compact 6×6 linear system:

$$\underbrace{\mathbf{J}^T \mathbf{R} \mathbf{J}}_{\mathbf{R}_{eff}} \mathbf{V} = - \underbrace{\mathbf{J}^T \mathbf{R} \mathbf{v}_{shape}}_{\mathbf{g}_{shape}}, \quad (20)$$

where $\mathbf{R}_{eff}$ is the effective resistance matrix of the entire multi-module assembly, and $\mathbf{g}_{shape}$ is the net propulsive wrench generated by the flagella. This formulation provides a compact framework for estimating the 3D translational and rotational velocities of rigidly docked assemblies with different topologies and coordination policies.

B. Effect of Actuation Frequency

The resistive-force-theory model in Sec. III-A predicts that, in the Stokes limit, the forward swimming speed U varies approximately linearly with the flagellar rotation rate

Ω_m (Eq. (16)) when the swimmer geometry, actuation kinematics, and hydrodynamic coefficients remain unchanged. To examine the frequency dependence experimentally and assess whether qualitative performance rankings were preserved across actuation rates, we characterized single-module helical swimmers at motor frequencies of 1.76 Hz and 2.31 Hz (Fig. 4A). For the long-flagellum anterior swimmer, the mean speed increased from 0.53 ± 0.05 cm/s at 1.76 Hz to 1.02 ± 0.13 cm/s at 2.31 Hz, while the corresponding posterior configuration increased from 0.35 ± 0.02 cm/s to 0.78 ± 0.11 cm/s.

Across both actuation locations and flagellum lengths, increasing the driving frequency consistently produced higher forward speeds while preserving the qualitative ordering between configurations (anterior $>$ posterior, long $>$ short). This trend is consistent with the model-predicted positive dependence of speed on rotation rate, although the measured increase was not quantitatively linear, likely reflecting frequency-dependent actuation kinematics, loading, and mild inertial effects. Because the qualitative rankings persisted across the tested frequency range and higher frequencies produced larger measurable displacements within the finite tank, all subsequent multi-module and gait-comparison experiments were standardized to 2.31 Hz. This provided a common experimental baseline while retaining viscosity-dominated flow conditions.

C. Single-Module Swimming Performance

Single-module experiments provide a baseline for how morphology (flagellum length, helical versus planar gait) and actuation location (anterior versus posterior) shape propulsion in isolation (SI Movie 00:12 - 00:27). These tests also justify the choice of two flagellum lengths and establish why most subsequent experiments focus on the long-flagellum configuration.

1) *Effect of Flagellum Length:* To examine the effect of flagellum length on propulsion performance, we varied the helical flagellum length between $L = 8.5$ cm (short) and $L = 15$ cm (long) across both actuation positions and frequencies, with results shown in Fig. 4A. For helical propulsion at 1.76 Hz, increasing flagellum length substantially increased forward speed in both actuation locations: in anterior mode, mean speed rose from 0.30 ± 0.03 cm/s (short) to 0.53 ± 0.05 cm/s (long), while in posterior mode it increased from 0.20 ± 0.02 cm/s to 0.35 ± 0.02 cm/s. This length-dependent gain persisted at 2.31 Hz, where the long flagellum achieved 1.02 ± 0.13 cm/s (anterior) and 0.78 ± 0.11 cm/s (posterior), compared to 0.58 ± 0.06 cm/s and 0.44 ± 0.05 cm/s for the short flagellum — representing speed gains of approximately 76% and 77% in anterior and posterior modes, respectively.

These results are consistent with resistive-force theory, which predicts that a longer flagellum generates greater net propulsive thrust for a fixed rotation rate, as the increased arc length amplifies the asymmetry between normal and tangential drag forces acting along the helical filament. Because the long flagellum yields a roughly 1.5–2-fold increase in speed relative to the short one across configurations,

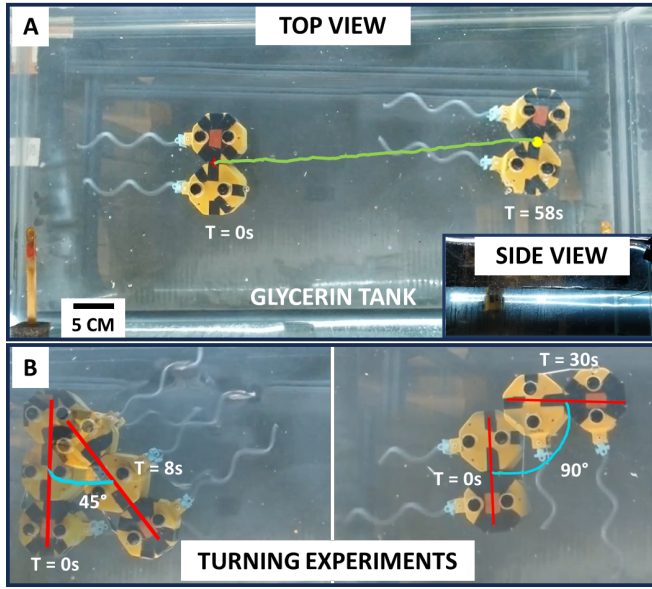


Fig. 3. **Representative Straight-line locomotion and turning maneuvers in glycerin.** (A) Top view of the acrylic tank showing the center-of-mass trajectory (green) of a side-connected dual-module swimmer between $t = 0$ s and $t = 58$ s, with an inset side view illustrating full submergence and a 5 cm scale bar for spatial reference. (B, left) Turning maneuver of a triple side-connected assembly, which rotates by approximately 45° over 8 s; red lines indicate the initial and final body orientations, and the cyan arc highlights the heading change. (B, right) Turning maneuver of a dual side-connected assembly with unequal flagellum lengths (long + short), executing an approximately 90° reorientation over 30 s.

we use the long configuration as the primary condition in subsequent multi-module and topology experiments to enhance measurable differences between assemblies.

2) Helical Versus Planar Gait: To compare biologically inspired gaits under matched geometry, we evaluated helical and planar traveling-wave propulsion for the long-flagellum module at 2.31 Hz (Fig. 4A-right). In anterior actuation, the helical gait achieved a mean speed of 1.02 ± 0.13 cm/s, whereas the planar gait reached only 0.43 ± 0.06 cm/s; in posterior actuation, the helical gait produced 0.78 ± 0.11 cm/s versus 0.36 ± 0.07 cm/s for the planar gait. Thus, for identical body geometry and similar waveform amplitude and wavelength, the helical mode outperforms the planar mode by approximately 40–60% in anterior configuration and by around 30% in posterior configuration.

This behavior is consistent with resistive-force-theory calculations, in which a rotating helix benefits from a strong coupling term B between rotation and translation (Eq. (10)), whereas the planar wave must rely on a traveling shape deformation to generate thrust. The performance of the helical gait in our robot aligns with observations in bacterial flagella, providing a quantitative reference for how much faster bundled, helical-like propulsion can be than planar beating at comparable length scales and actuation rates.

3) Anterior Versus Posterior Actuation: Across all single-module conditions, anterior (puller-like) actuation yielded higher speeds than posterior (pusher-like) actuation for the same flagellum length and gait (Fig. 4. For the long helical

flagellum at 2.31 Hz, anterior actuation reached 1.02 ± 0.13 cm/s compared to 0.78 ± 0.11 cm/s for posterior actuation, while for the planar gait the corresponding speeds were 0.43 ± 0.06 cm/s and 0.54 ± 0.07 cm/s. At 1.76 Hz, the same ordering holds, with anterior helical speeds exceeding posterior speeds by roughly 50% for both long and short flagella.

These results suggest that anterior role allocation improves propulsion by reducing the effective drag penalty at the leading edge, as well as favorably redistributing thrust and modifying near-field hydrodynamic interactions with the head.

D. Multi-Module Forward Swimming: Topology and Module Roles

We next examined how mechanical coupling between identical modules (via face-to-face and side-by-side magnetic connections) modifies propulsion at 2.31 Hz (Fig. 4B, SI Movie 00:28 - 00:50). These experiments address three questions: (i) how speed scales with the number of modules N , (ii) how assembly topology (face-to-face versus side-by-side) reshapes effective drag and thrust distribution, and (iii) how allocating pulling versus pushing roles across modules affects performance.

1) Dual-Module Assemblies: For dual-module assemblies with long helical flagella at 2.31 Hz, pairing two anterior-acting modules yielded a mean speed of 1.00 ± 0.09 cm/s, comparable to the single-module anterior speed of 1.02 ± 0.13 cm/s, indicating that simply adding a second puller in a side-connected topology does not significantly increase speed. In contrast, two posterior-acting modules in the same topology swam at 0.57 ± 0.04 cm/s, which is markedly slower than the single posterior module (0.78 ± 0.11 cm/s), suggesting that clustering pushers behind a larger body amplifies drag more than thrust. Short-flagellum dual swimmers exhibited the same qualitative trend, with anterior and posterior speeds of 0.57 ± 0.05 cm/s and 0.32 ± 0.03 cm/s, respectively.

When the two modules were connected in a face-to-face topology along their propulsion axis, the long-flagellum helical assembly achieved a mean speed of 1.22 ± 0.14 cm/s, outperforming both the single-module and dual side-connected anterior configurations. The corresponding long-flagellum planar face-to-face assembly reached 0.62 ± 0.05 cm/s, consistent with the ~ 40 – 60% speed penalty of planar over helical propulsion observed at the single-module level. Both face-to-face results indicate that aligning modules collinearly reduces lateral drag and allows the combined thrust to act more directly along the swimming axis.

2) Triple-Module Assemblies and Pusher–Puller Combinations: Triple-module experiments with long helical flagella at 2.31 Hz highlight that distributing the roles of pushing and pulling across modules can either improve or degrade performance, even for a fixed topology. A chain of three anterior (puller-like) modules in a side-connected arrangement reached 1.48 ± 0.27 cm/s, representing a substantial increase relative to the single-module anterior speed of

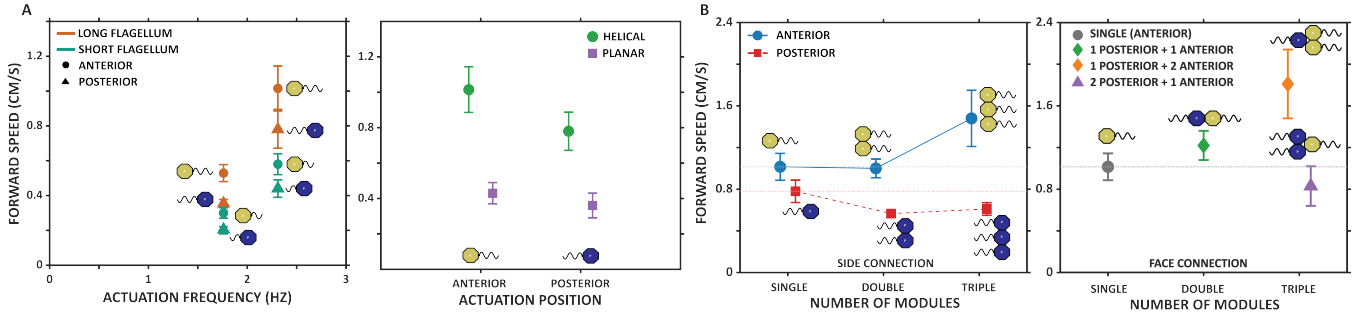


Fig. 4. **Swimming performance across single- and multi-module configurations.** (A, left) Forward speed at 1.76 Hz and 2.31 Hz for long and short helical flagella in anterior and posterior actuation. (A, right) Gait comparison at 2.31 Hz for the long flagellum; (B, left) Side-connected assemblies ($N = 1-3$); (B, right) Face-to-face assemblies ($N = 1-3$); Dotted lines indicate the single-module anterior baseline. Error bars denote mean $\pm$ SD over at least three trials.

1.02 ± 0.13 cm/s, while three posterior (pusher-like) modules achieved only 0.61 ± 0.06 cm/s, slightly faster than the dual posterior case but still below the single posterior swimmer.

In a face-to-face topology, mixed-role configurations produced even more pronounced differences. A chain with one posterior pusher and two anterior pullers attained 1.81 ± 0.33 cm/s, making it the fastest configuration tested and surpassing the all-anterior triple chain by roughly 20–25%. By contrast, the complementary configuration with two pushers and one puller swam at 0.83 ± 0.19 cm/s, close to the speed of a single anterior module despite having three active flagella. When only the two posterior modules were active in the same chain, the speed dropped further to 0.49 ± 0.07 cm/s, and with only a single posterior module active in the multi-body assembly, the speed was just 0.273 ± 0.004 cm/s.

These findings demonstrate that, at low Reynolds number, more actuators do not automatically translate into faster swimming; instead, the net performance depends sensitively on the placement of thrust sources relative to the composite body and among themselves. Configurations that emphasize anterior pulling while limiting trailing pushers exploit favorable hydrodynamic coupling and reduced drag, whereas bundles of pushers behind a large assembly effectively increase the resistance matrix without a commensurate gain in useful thrust, analogous to inefficient flagellar bundling in biological systems.

E. Turning via Phase Asymmetry and Partial Activation

Beyond forward propulsion, a key objective of this study was to determine whether modular docking enhances steering capability and to quantify how turning can be achieved through coordination and structural variation.

Turning was evaluated at 2.31 Hz under multiple strategies for breaking symmetry within the assembly (SI Movie 00:51 - 00:59). These included: (i) phase differences between laterally separated modules, (ii) unequal flagellar lengths, and (iii) selective activation of connected modules.

1) Dual-Module Turning: Turning experiments with dual-module assemblies reveal that phase coordination between modules is a more effective steering mechanism than selective deactivation. Two long-flagellum modules with posterior

actuation in an anti-phase configuration, where each module's flagellum rotates out of phase with the other, achieved the highest dual-module turning rate of 4.46 ± 2.06 $^{\circ}$ /s (0.078 ± 0.036 rad/s), generating a strong yaw moment through asymmetric thrust distribution across the assembly. A mixed-length pair (one short, one long flagellum), both active with posterior actuation in an in-phase configuration, turned at a lower rate of 2.81 ± 1.77 $^{\circ}$ /s (0.048 ± 0.031 rad/s); the reduced turning performance here arises not from phase asymmetry but from the geometric mismatch between flagella, which produces unequal drag on either side of the assembly without a controlled phase differential.

A third dual-module strategy (long-flagellum anterior actuation with one module active and one inactive) yielded a turning rate of 2.36 ± 1.08 $^{\circ}$ /s (0.041 ± 0.019 rad/s). While slower than the anti-phase posterior case, this approach steers the assembly by creating a force imbalance rather than a phase imbalance, suggesting a simpler control strategy at the cost of reduced turning authority.

2) Triple-Module Coordinated Turning: The highest turning rates were observed in the three-module assemblies with mixed-phase anterior actuation. When one module oscillated in anti-phase relative to the two remaining in-phase anterior modules, the assembly achieved a mean turning rate of 4.61 ± 2.03 $^{\circ}$ /s (0.081 ± 0.035 rad/s), marginally exceeding the best dual-module turning rate while operating in a larger, higher-drag structure. This result demonstrates that introducing a single phase-shifted module into an otherwise synchronized chain is sufficient to generate a yaw moment comparable to full anti-phase dual actuation, while the two in-phase modules continue to contribute net forward thrust.

Together, these turning results establish that yaw authority in multi-module assemblies is governed primarily by the degree of phase asymmetry across active modules rather than by module count alone. The same reconfigurable platform that achieves maximum forward speed through puller-dominated, face-to-face chains can be steered by redistributing actuation phases, demonstrating that topology and coordination serve as independent control inputs for shaping both translational and rotational motion in viscosity-dominated environments.

IV. CONCLUSION

This work presented a systematic experimental and theoretical investigation of how topology and coordination govern locomotion in a reconfigurable modular swimming robot in a viscous environment. Using centimeter-scale flagellated modules assembled into configurations of $N = 1$ to 3 units in glycerin, we showed that helical propulsion outperforms planar traveling-wave actuation by 40–60% under matched geometry, that anterior puller-like actuation consistently exceeds posterior pusher-like actuation across all configurations, and that module count alone does not determine speed; role allocation does. The fastest configuration, a triple face-to-face chain with one pusher and two pullers, achieved 1.81 ± 0.33 cm/s, a 78% improvement over a single module, while an equivalent three-module assembly with roles reversed swam at less than half that speed. Turning experiments further demonstrated that yaw can be generated through multiple forms of symmetry breaking, including phase asymmetry, unequal flagellum length, and selective activation, with anti-phase dual and mixed-phase triple configurations achieving peak turning rates near $4.5^\circ/\text{s}$.

The present study has some limitations. Residual confinement effects from the finite tank cannot be fully excluded for larger assemblies, and for triple-module configurations at 2.31 Hz, the Reynolds number approaches unity, introducing mild inertial corrections beyond the RFT model. The multi-module Stokes mobility model remains preliminary and requires further development to reliably predict quantitative behavior across larger and mixed-role assemblies.

Future work will extend the characterization to $N > 3$ modules and asymmetric topologies, improve the multi-body hydrodynamic model, and examine how flagellar flexibility affects propulsion and turning. The RFT analysis will also be extended to more complex flagellar waveforms, with geometric mechanics used to study gait design and control. Closed-loop steering based on heading feedback will move the platform beyond the open-loop maneuvers reported here. We also plan to miniaturize the platform toward sub-centimeter scales, where the Stokes-flow assumptions are more accurate, and test it in non-Newtonian fluids relevant to biological environments.

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