Independent Control of Two Millimeter-Scale Soft-Bodied Magnetic Robotic Swimmers

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***Abstract*— This paper presents a method to independently control two millimeter-scale soft-bodied magnetic swimmers, with nominal dimensions of $1.5 \times 4.9 \times 0.06$ mm, for applications in microrobotics. The two swimmers under control are required to have different directions of net magnetic moment (not parallel or antiparallel). The swimmer's speed depends on its relative angle with the actuation magnetic field. With a fixed heading difference between two swimmers, the single global actuation field forms different relative angles with two swimmers. By manipulating these two relative angles, different velocities can be induced in the two swimmers. Theoretically, any ratio value can be achieved between the two swimmers' speeds. In experiments, a relatively accurate velocity ratio can be obtained when both swimmers have nonzero speeds and one swimmer is no more than twice as fast as the other. Adding the control over the strength of actuation field, two swimmers can obtain independent velocities within an range. Two feedback controllers are proposed to manipulate two such swimmers to arrive at independent global points (positioning) and move along paths (path following). Type I Sequential Controller manipulate two swimmers to move to their respective goals in sequence, while Type II Parallel Controller moves both swimmers simultaneously. Demonstrations show two swimmers are controlled by the proposed controllers to follow the path defined by the letters "UT".**

I. INTRODUCTION

Tetherless mobile microrobots can perform tasks remotely in small and enclosed environments. Previous studies showed the wide range of potential applications of microrobots, including microobject manipulation and transportation [1], healthcare tasks [2], and scientific tools [3]. How to wirelessly control and actuate microrobots remains an open-ended problem in the community of microrobotics. Among the many strategies that have been proposed for this problem [4]–[6], magnetic fields become a common choice. Magnetic fields can penetrate most materials, generate both forces and torques on magnetic materials, and are easy and safe to generate and manipulate. Additionally, the setup to generate magnetic fields using electric coils has a commonly followed standard, allowing different magnetic microrobots to be controlled by the same setup. Many microrobots have been proposed employing magnetic torques for actuation, some of which are soft-bodied microrobots [6]–[8]. Soft-bodied microrobots have distinct advantages over traditional rigid microrobots, including the ability of changing shape for propulsion, offering gentle interactions with their working environments, and being less prone to damage.

The intrinsic small size of microrobots urge the research in controlling multiple microrobots to perform tasks as a team. A straightforward approach to control multiple microrobots is providing different signal, i.e., localized control input, to each individual. For example, up to ten opto-thermocapillary flow-addressed bubble (OFB) microrobots were manipulated by focusing laser beams into different patterns on a horizontal two-dimensional (2D) plane [9]. However, this method is difficult to be further scaled down because localized signals are more challenging to generate with a smaller resolution. Another option to control multiple microrobots, which doesn't have difficulties in being scaled down, is inducing a different response from each agent using the same global control signal. Differences in the magnetization strengths and geometric dimensions were utilized to configure three magnetic microrobots into independent global positions [10]. Other physical properties of microrobots, such as resonance frequencies, step-out frequencies, and turning-rates, have also been tested to differentiate an individual agent from a group of microrobots [11]–[13].

This paper presents a method to independently control two millimeter-scale soft-bodied magnetic swimmers. The concept of an individual swimmer of this type was first reported in [6] and further characterized in [14] with preliminary results of controlling two swimmers. The swimmers can swim both at the air-water interface and in the water [14]. This paper focuses on the problem of independently controlling the positions of two swimmers, which move at the air-water interface, and their velocity ratio ζ, defined as $\zeta = v_1/v_2$ where v_1 and v_2 are the speeds of two swimmers. The proposed control method takes advantage of the difference in the headings of net magnetic moments of two swimmers, requiring the directions of net magnetic moments of two swimmers to be different. This method is able to manipulate two swimmers to achieve different velocity values and move them to independent positions on a 2D horizontal plane, with the limitation that the relative angle between two swimmers' headings cannot be altered. Two feedback controllers are proposed: Type I Sequential Controller and Type II Parallel Controller, which control two swimmers to move towards their respective goals in sequence or simultaneously. This paper introduces a basic method for controlling multiple swimmers using a single global magnetic field. It is expected that this work can be applied for the control of multiple microrobots to cooperate in tasks.

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II. Concepts and Definitions

The swimmer studied in this work is composed of elastic polymer with magnetic particles embedded. The magnetic particles are magnetized to form a sinusoidal magnetization profile along the swimmer's body. When placed at the air-water interface inside a uniform magnetic field, the swimmer experiences magnetic torques, surface tension forces, and buoyancy, among which the magnetic torques play the dominating role in deforming the swimmer. The strength of magnetic field is smaller than the coercivity of the magnetic materials in the swimmer, and so the swimmers' magnetization will not be altered by the applied magnetic field. This section reviews the working principle of the swimmer, which has been introduced in detail in [14], and lays the foundation for controlling two swimmers.

A. Principles of Swimmer

The concept of swimmer in this work is depicted in Fig. 1, with the definitions of two Cartesian frames xyz and $x'y'z'$, which are the global frame of the workspace and the local frame of the swimmer, respectively. As shown in Fig. 1(a), the swimmer has a sinusoidal magnetization profile $\mathbf{M}$ along its body with a constant magnitude and a rotating direction, which can be described by

$$\mathbf{M}(x') = M\cos\left(\frac{2\pi x'}{\lambda}\right)\hat{\mathbf{i}}' + M\sin\left(\frac{2\pi x'}{\lambda}\right)\hat{\mathbf{k}}', \quad (1)$$

where M is the constant magnitude of magnetization, and λ is the wavelength of the sinusoidal magnetization profile. Vectors $\hat{\mathbf{i}}'$ and $\hat{\mathbf{k}}'$ are the unit vectors of the local axes x' and z'. When placed in a uniform magnetic field, the swimmers' magnetization forms a sinusoidally changing angle with the field, and generate magnetic torques with corresponding magnitudes. Together with the surface tension forces and buoyancy, the magnetic torques deform the swimmer's body into an approximate sinusoidal wave. When the applied magnetic field rotates in a vertical plane, the angle between the field and the magnetization of swimmer change continuously, causing the swimmer's body to mimic a traveling wave and generate propulsive forces to make the swimmer swim.

Here the wavelength λ is set to be equal to the swimmer's length L, i.e., the swimmer has a full period of sinusoidal magnetization. Therefore, $\mathbf{M}(s)$ should sum up to zero, meaning the swimmer has a zero net magnetic moment, i.e., $\int_0^L M\mathrm{d}x' = \mathbf{0}$. However, the swimmers tested rarely have exactly zero net magnetic moment, as a result of inaccuracies in the fabrication process. The angle from the positive x'-axis of a swimmer to its net magnetic moment's projection on the x'-y' plane is defined as angle ϕ. It should be noted that all the angles and angle differences defined hereafter will be automatically wrapped into the range of $(-\pi, \pi]$ for clarity. Utilizing the existence of this nonzero net magnetic moment, the swimmer's heading can be steered by a small constant magnetic field $\mathbf{B}_\mathrm{s}$ in the x-y plane. Therefore, the magnetic field applied in the workspace is a superposition of a rotating field $\mathbf{B}_\mathrm{a}$ for actuation and a constant field $\mathbf{B}_\mathrm{s}$ for steering. As shown in Fig. 1(c), the direction of $\mathbf{B}_\mathrm{s}$ in

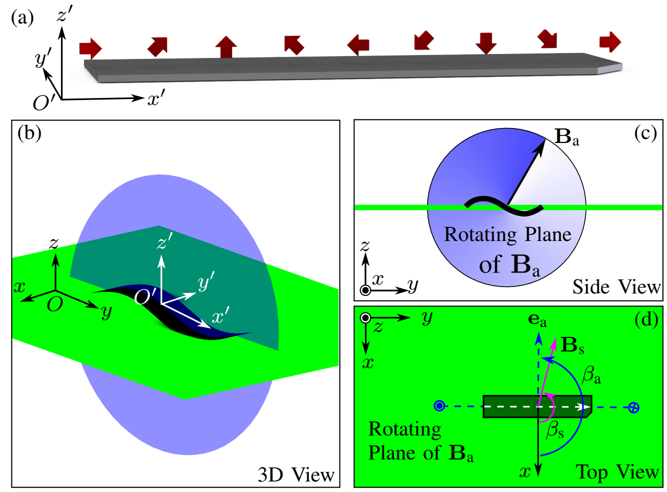

Fig. 1. Conceptual view of the swimmer with a sinusoidal magnetization profile, actuated by a rotating field $\mathbf{B}_\mathrm{a}$ and steered by a constant field $\mathbf{B}_\mathrm{s}$. A swimmer's model is shown in (a) together with arrows representing the magnetization direction along the swimmer's body. Views of a swimmer moving under the control of $\mathbf{B}_\mathrm{a}$ and $\mathbf{B}_\mathrm{s}$ are shown in (b), (c), and (d) from three different viewpoints. The actuation field $\mathbf{B}_\mathrm{a}$ rotates in a vertical plane that is denoted in blue. Whereas the steering field $\mathbf{B}_\mathrm{s}$ is applied in the horizontal plane that is colored in green.

the x-y plane is given by β_s, with respect to the positive x axis. The direction of the rotating plane of $\mathbf{B}_\mathrm{a}$ is defined by a direction vector $\mathbf{e}_\mathrm{a}$ according to the right-hand-rule, whose direction in the x-y plane is given by angle β_a.

B. Foundation for Controlling Two Swimmers

The proposed swimmers move in a non-holonomic fashion, i.e., they only move forward and backward along their long axes (x'-axes). A swimmer's speed is affected by its orientation relative to the actuation field $\mathbf{B}_\mathrm{a}$. This orientation is described by an angle γ from the swimmer's local x' axis to the direction vector $\mathbf{e}_\mathrm{a}$ of field $\mathbf{B}_\mathrm{a}$, which is named the relative actuation angle, and calculated by

$$\gamma = \beta_\mathrm{a} - \beta_\mathrm{s} + \phi. \quad (2)$$

A swimmer achieves its maximum positive and negative speeds when $\gamma = \pi/2$ and $-\pi/2$, respectively. In these cases, the plane of actuation field $\mathbf{B}_\mathrm{a}$ aligns with the swimmer and $\mathbf{B}_\mathrm{a}$ actually rotates in the swimmer's local x'-z' plane. As the plane of $\mathbf{B}_\mathrm{a}$ deviates from the swimmer's x'-z' plane, the swimmer's velocity decreases. Fig. 2(a) plots the experimental data of three swimmers' speeds against the relative actuation angle γ, suggesting an approximate sinusoidal relationship between a swimmer's velocity and γ that can be expressed as

$$v(\gamma) = v_0 \sin(\gamma), \quad (3)$$

where v_0 is a nonzero scaling factor calculated by fitting speed data to a sinusoidal curve. Thus, we can consider the swimmer's speed to be proportional to the maximum value of the projected magnitude of $\mathbf{B}_\mathrm{a}$ on the swimmer's x' axis.

For the case of two swimmers, the difference between the directions of their net magnetic moments is defined as the

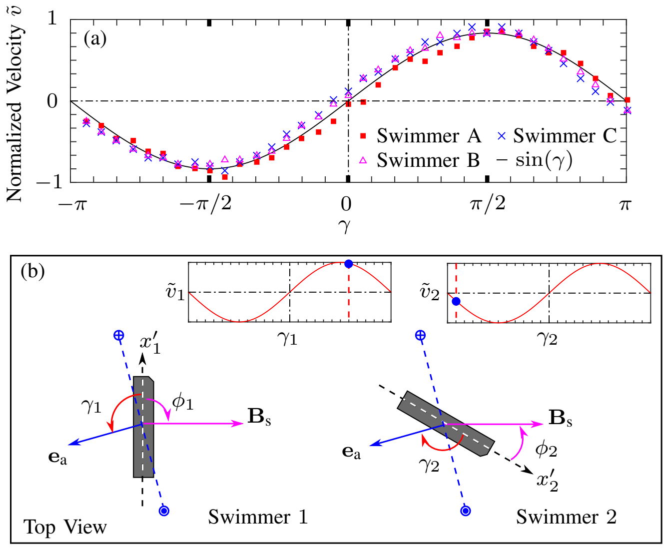

Fig. 2. Illustration of the foundation for controlling two swimmers. (a) The normalized velocity $\tilde{v}$ of a swimmer varies with the value of γ. The experimental data, which are average values of three trails, are shown together with a sinusoidal curve. The speed data of each trail is fitted with $v(\gamma) = v_0 \sin(\gamma)$ to determine v_0. The normalized velocity is calculated as $\tilde{v} = v/v_0$. (b) Two swimmers with different directions of net magnetic moments ($\phi_1 \neq \phi_2$) assume different headings under the same steering field $\mathbf{B}_\mathrm{s}$ and thus form different angles ($\gamma_1 \neq \gamma_2$) with the same global actuation field $\mathbf{B}_\mathrm{a}$. The insets show the working points of each swimmer on its $\tilde{v}$ vs. γ graph.

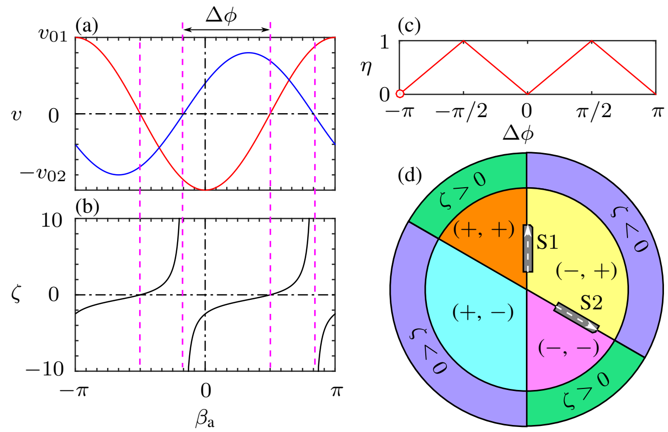

Fig. 3. Illustration of the velocity ratio ζ between two swimmers and the controllability η. The speeds of swimmers S1 and S2, i.e., v_1 and v_2, are plotted in (a) against β_a, with red represents v_1 and blue stands for v_2. The two swimmers' velocity ratio $\zeta = v_1/v_2$ is shown in (b). (c) The value of controllability η is plotted against the heading difference between two swimmers $\Delta\phi$. (d) A circular plane is divided into four "quadrants" to illustrate the meaning of controllability η. The signs in parentheses mark the movement directions of two swimmers when direction vector $\mathbf{e}_\mathrm{a}$ of $\mathbf{B}_\mathrm{a}$ is within each quadrant: "+" means moving forward while "−" denotes swimming backward. The range of velocity ratio ζ is labeled in the outer circle of each quadrant.

heading difference $\Delta\phi = \phi_2 - \phi_1$. When $\Delta\phi \neq 0$, the two swimmers assume different headings with an angle difference of $\Delta\phi$ when $\mathbf{B}_\mathrm{s}$ is applied. Because the applied magnetic field does not alter swimmers' magnetization profiles, the orientation difference $\Delta\phi$ between two swimmers is a constant. Therefore, the same global actuation field $\mathbf{B}_\mathrm{a}$ forms different relative actuation angles with the two swimmers, i.e., $\gamma_1 \neq \gamma_2$, resulting in different speeds from the two swimmers, as illustrated in Fig. 2(b). By controlling the directions and amplitudes of $\mathbf{B}_\mathrm{s}$ and $\mathbf{B}_\mathrm{a}$, the speeds of two swimmers will generate different values of velocity ratio ζ.

This section reviews the basic working principles of swimmers and introduces the foundation for controlling two swimmers independently. For a more detailed characterization of a single swimmer's behavior, readers are referred to our previous work [14]. In the next section, the capabilities and difficulties of this control method are characterized.

III. Characterization

This section characterizes the problem of controlling two swimmers. It is shown here that the two swimmers can theoretically achieve an arbitrary velocity ratio ζ. Additionally, a variable η to quantitatively measure the easiness of controlling two swimmers is defined.

A. Velocity Ratio and Values of Two Swimmers

As indicated by Fig. 2(a), the speed v of a swimmer is sinusoidally dependent on its relative actuation angle γ. When two swimmers are placed in the same $\mathbf{B}_\mathrm{s}$, the angle difference between their headings is $\Delta\phi$. If the two swimmers' velocities are plotted against β_a, the phase difference between the two curves is also $\Delta\phi$. To illustrate the relationship between the velocities of two swimmers, swimmer S1 with $\phi_1 = -\pi/2$ and swimmer S2 with $\phi_2 = \pi/6$ are taken as an example. It is also known that the velocities of S1 and S2 can be expressed by $v_1 = v_{01}\sin(\gamma_1)$ and $v_2 = v_{02}\sin(\gamma_2)$, respectively. When $\mathbf{B}_\mathrm{s}$ is applied along the $+x$ direction, i.e., $\beta_\mathrm{s} = 0$, the two swimmers' speeds are shown in Fig. 3(a) with respect to β_a. Fig. 3(b) shows the velocity ratio ζ of two swimmers.

As indicated in Fig. 3(b), ζ ranges from $-\infty$ to ∞, except when $\Delta\phi = 0$ or π, in which cases ζ can only be $0/0$ or v_{01}/v_{02}. By controlling the values of β_a and β_s, an arbitrary velocity ratio ζ can be achieved theoretically. Nevertheless, limited by the noise in a physical system, an accurate velocity ratio can be achieved only when both swimmers have nonzero speeds and one swimmer is no more than twice as fast as the other. It is also observed in experiments that the swimmer's velocity increases with the strength of the magnetic field within an range. Therefore, arbitrary velocity ratio can scale to arbitrary velocity values by changing the strength of actuation field.

B. Controllability

The preceding part has shown that two swimmers can achieve different velocities by choice of the input field angles β_a and β_s, as long as the directions of their net magnetic moments are not parallel or anti-parallel, i.e., $\Delta\phi \neq 0$ or π. However, the level of difficulty in obtaining a desired velocity ratio ζ in the presence of noises and errors varies with the $\Delta\phi$. To quantitatively evaluate this level of difficulty, a variable η named controllability is defined as

$$\eta = \frac{2 \times \min\left(|\Delta\phi|,\, \pi - |\Delta\phi|\right)}{\pi}, \tag{4}$$

where function min() returns the minimum value of its two inputs. The value of η is plotted against $\Delta\phi$ in Fig. 3(c), which suggests that a two-swimmer set with $\Delta\phi = \pm\pi/2$ has the highest controllability ($\eta = 1$, easiest to control independently) while a set with $\Delta\phi = 0$ or π has the lowest controllability ($\eta = 0$, impossible to control independently).

The meaning of η can be intuitively perceived from Fig. 3(d), in which a circular plane is divided into four parts by the local x' axes of two swimmers, similar with the four quadrants of a coordinate frame. Diagonal quadrants correspond to the same range of velocity ratio λ. In the case of $\Delta\phi = \pm\pi/2$, the four quadrants have identical areas. Otherwise, two diagonal quadrants are compressed while the other two being expanded. When the areas of a pair of diagonal quadrants are compressed, λ in the corresponding range becomes more sensitive to the change of the direction of $\mathbf{B}_{\mathrm{a}}$, resulting in a higher requirement to the input accuracy and a lower value of the controllability η. In the uncontrollable cases ($\Delta\phi = 0$ or π), this four-quadrant structure collapses, and the two swimmers will have a fixed ζ value whichever direction $\mathbf{B}_{\mathrm{a}}$ is applied, resulting in $\eta = 0$. Thus, the relative angle $\Delta\phi$ between two swimmers' net magnetic moments affects the level of difficulty in controlling two swimmers independently, which is described by the value of η. The most desirable case is when two swimmers have perpendicular magnetic moments, i.e., $\Delta\phi = \pm\pi/2$, while the worst case happens when the net magnetic moments of two swimmers are parallel or antiparallel, i.e., $\Delta\phi = 0$ or π.

IV. Feedback Controllers

Based on the capability of inducing independent velocities from two swimmers, controllers are designed to independently position two swimmers at a horizontal 2D plane. Since the relative heading difference $\Delta\phi$ of two swimmers is a fixed value, the two swimmers cannot move directly towards their respective goals simultaneously in most cases. The two controllers proposed here deal with this problem in two ways: Type I Sequential Controller moves one swimmer at a time, while Type II Parallel Controller actuates two swimmers to zigzag to their respective goals simultaneously.

A. Navigation and Control Geometry

Two fictitious swimmers S1 and S2 with $\phi_1 = \pi/12$ and $\phi_2 = \pi/2$ are drew in Fig. 4 to illustrate the definitions required by the discussion here. Points P and G stand for the present and goal positions of a swimmer, respectively. Goal vector $\mathbf{r}$ points from point P to G. Swimmer S1 (S2) can be brought into alignment with $\mathbf{r}_1$ ($\mathbf{r}_2$) by a steering field $\mathbf{B}_{\mathrm{s}}$ applied along the line l_1 (l_2). Because a swimmer can move both forward and backward, the field $\mathbf{B}_{\mathrm{s}}$ can be applied along either direction of line l_1 (l_2). If l_1 coincides with l_2, S1 and S2 will align with their respective goal vectors simultaneously when $\mathbf{B}_{\mathrm{s}}$ is along l_1 or l_2. In this case, the two controllers produce the same result: The two swimmers move directly towards their goals simultaneously in straight lines. By selecting the direction of $\mathbf{B}_{\mathrm{a}}$, the velocities of two swimmers are regulated such that both swimmers reach their

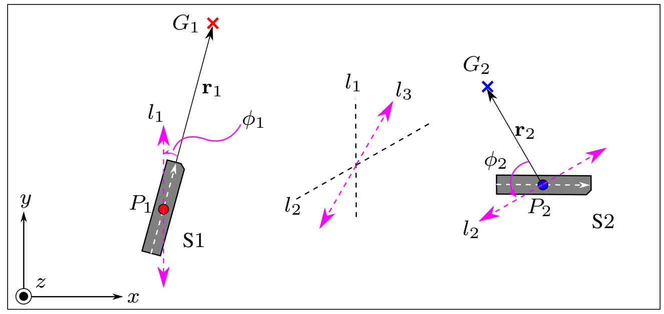

Fig. 4. Definitions of related variables for the proposed two controllers.

goals at the same time. When l_1 does not coincide with l_2 (as is shown in Fig. 4), S1 and S2 are not able to align with $\mathbf{r}_1$ and $\mathbf{r}_2$ simultaneously, no matter which direction $\mathbf{B}_{\mathrm{s}}$ is applied. This is the case in which the two controllers perform differently.

B. Type I Sequential Controller

When l_1 does not coincide with l_2, Type I Sequential Controller controls the two swimmers to reach their respective goals in sequence. This controller first compares the distances between the two swimmers' present and goal positions, i.e., $|\mathbf{r}_1|$ and $|\mathbf{r}_2|$. Then, the steering field $\mathbf{B}_{\mathrm{s}}$ is applied in a direction such that the swimmer with a longer distance (S1 in the example) aligns with its goal. The direction vector $\mathbf{e}_{\mathrm{a}}$ of actuation field $\mathbf{B}_{\mathrm{a}}$ is aligned with the other swimmer S2 ($\gamma_2 = 0$), so that the actuation field rotates in a plane that is perpendicular to the local x' axis of S2. As a result, the actuation field $\mathbf{B}_{\mathrm{a}}$ only propels S1 to move towards its goal, while keeps S2 stationary. After S1 has reached its goal, the controller applies the $\mathbf{B}_{\mathrm{s}}$ to align S2 with its goal, and applies $\mathbf{B}_{\mathrm{a}}$ such that S2 moves towards its goal while S1 stops.

C. Type II Parallel Controller

When both swimmers need to move, i.e., $|\mathbf{r_1}| \neq 0$ and $|\mathbf{r_2}| \neq 0$, Type II Parallel Controller manipulates two swimmers to reach their respective goals in parallel. This controller selects the directions of $\mathbf{B}_{\mathrm{s}}$ and $\mathbf{e}_{\mathrm{a}}$ such that $|\mathbf{r_1}|$ and $|\mathbf{r_2}|$ are reduced simultaneously and in a balanced manner. In the cases when the directions of l_1 and l_2 are not identical, $\mathbf{B}_{\mathrm{s}}$ is selected to be along the angle bisector l_3 of the smaller angle formed by l_1 and l_2, as shown in Fig. 4. This choice is a compromise that not only minimizes the sum of the deviation angles of S1 and S2 from $\mathbf{r}_1$ and $\mathbf{r}_2$, but also makes the two deviation angles equal to each other. The decision of which side of l_3 to use as the new direction of $\mathbf{B}_{\mathrm{s}}$ is made based on the criterion that the change between the new and the previous directions of $\mathbf{B}_{\mathrm{s}}$ should be minimized.

After the direction of $\mathbf{B}_{\mathrm{s}}$ is selected, the controller selects the direction vector $\mathbf{e}_{\mathrm{a}}$ of $\mathbf{B}_{\mathrm{a}}$ such that the velocity ratio of two swimmers is equal to their distance ratio, i.e.,

$$\zeta = \frac{|\mathbf{r}_1|}{|\mathbf{r}_2|} = \frac{|v_{01}\sin(\gamma_1)|}{|v_{02}\sin(\gamma_2)|} = \frac{v_{01}|\sin(\gamma_1)|}{v_{02}|\sin(\Delta\phi + \gamma_1)|}. \quad (5)$$

For two controllable swimmers, $\sin(\Delta\phi) \neq 0$, and it is also known that $|\mathbf{r_1}| \neq 0$ and $|\mathbf{r_2}| \neq 0$, we can get

$$\gamma_1 = \cot^{-1}\left(\frac{\pm\frac{|\mathbf{r}_2|v_{01}}{|\mathbf{r}_1|v_{02}} - \cos(\Delta\phi)}{\sin(\Delta\phi)}\right). \tag{6}$$

The variable γ_1 have four values from (6), corresponding to the four possible combinations of the two swimmers' moving directions. Only one of the four γ_1 values corresponds to the movement that reduces both swimmers' distances to their goals, and this γ_1 value is used to determine the rotation direction of $\mathbf{B}_\mathrm{a}$ as $\beta_a = \beta_\mathrm{s} - \phi_1 + \gamma_1$.

D. Compatibility with Path Following Tasks

Both of the proposed controllers are designed for the independent positioning of two swimmers, and only the swimmers' final positions are considered. Nevertheless, these two controllers can also be used for path following tasks, with the desired path being approximated by line segments. Type I Sequential Controller can be adapted directly for path following tasks, since swimmers move in straight lines and the deviations of swimmers from the desired path is negligible. With Type II Parallel Controller, a swimmer zigzags towards its goal with its deviation, which is calculated with respect to the line connecting the swimmer's initial and goal positions, goes up and down and can be considerably big. As a result, a deviation limiter needs to be imposed on Type II Parallel Controller for path following tasks.

V. Experimental Demonstrations

This section briefly introduces the fabrication procedures and experimental setups for swimmers (more details in [14]), and present the experimental results of the proposed two controllers and the deviation limiter.

A. Fabrication of Swimmers and Experimental Setup

Swimmers are composed of flexible elastomer (Ecoflex 00-50, density 1.07 g/cm^3, Young's modulus 83 kPa) with unmagnetized magnetic powders (MQFP-15-7, NdPrFeB, Magnequench) embedded at a mass ratio of 1:1. The elastomer cures in the gap (0.06 mm) between two acrylic plates. Swimmers are cut from the elastomer sheet by a laser cutter (Epilog Laser Mini 40 Watt) with nominal dimensions of 1.5×4.9 mm. Rolled into circles, swimmers are magnetized in a uniform magnetic field (1 T), which programs a sinusoidal magnetization profile into the swimmer's body.

The experimental drive setup includes an electromagnetic coil system with three pairs of wire loops and three analog servo drives (30A8, Advanced Motion Controls), a signal source based on a multifunction analog/digital I/O board (Model 826, Sensoray), a 60 fps camera (FO134TC, FOculus) mounted atop the workspace, and a computer with custom programs. Each pair of wire loops in the coil system is arranged in an approximate Helmholtz configuration, resulting in a uniform magnetic field up to 15 mT in the workspace located at the geometric center of the coil system.

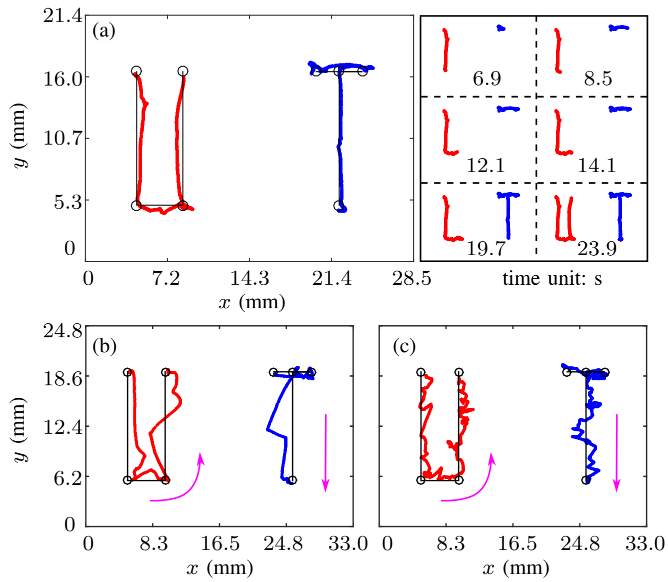

Fig. 5. Paths of two swimmers in "UT" following experiments. Goal points and desired paths are marked by black circles and lines, respectively. Center points of two swimmers are represented by red (S1) and blue (S2) dots. Results of Type I Sequential Controller are shown in (a) with small figures illustrating the moving order of swimmers. Results of Type II Parallel Controller without a deviation limiter are plotted in (b). Swimmers' paths under the control of Type II Parallel Controller and a deviation limiter with $\rho = 0.05$ bl. are shown in (c). Video is available in supplementary materials.

B. Demonstrations of Two Controllers

Two swimmers, S1 with $\phi_1 = 127°$ and S2 with $\phi_2 = -164°$, were controlled to follow a series of goal points along the path of letters"UT", to demonstrate the efficacies of the proposed two controllers. Fig. 5 shows the experimental results with clear distinctions between the two controllers. With Type I Sequential Controller, only one swimmer is actuated at a time, which moves towards its goal in a straight line. As a result, the distance traveled by each swimmer is minimized. It should be noted that the moving swimmer does not necessarily swim at its maximum speed, because the rotation direction of actuation field is aligned with the other swimmer to keep it stationary. For Type II Parallel Controller, both swimmers zigzag simultaneously to their respective goals. Since this controller does not consider the swimmers' deviations, the two swimmers deviate obviously from the desired path, as shown in Fig. 5(b).

C. Type II Parallel Controller with Deviation Limiter

Adding a deviation limiter, the Type II Parallel Controller can work for path following tasks, with the desired path being approximated by line segments. The goal points for swimmers are the connecting points of line segments. Before the swimmers begin to move towards the next group of connecting points of line segments, the deviation limiter predicts the next turning points of the two swimmers. If at least one turning point is outside the allowable deviation range ρ, the limiter re-positions the turning points so that both of them are within ρ. Then, the deviation limiter passes the two turning points to Type II Parallel Controller as its next goal

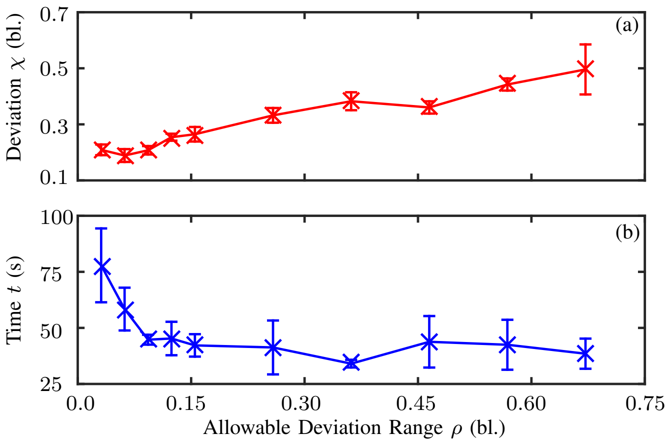

Fig. 6. Experimental data showing the effect of the allowed deviation range ρ on the total deviation χ (a) and the path completion time t (b).

points. After both swimmers have arrived at the goal points specified by the deviation limiter, the limiter specifies next group of intermediate goal points, until two swimmers reach their "original" goal points, i.e., the connecting points of line segments. Thus, the actual deviations of two swimmers are limited within a range, as shown in Fig. 5(c).

The deviation limiter is characterized by studying the effect of ρ on χ and t, where χ is the root-mean-square (rms) value of the sum of two swimmers' deviations from the desired paths and t is the path completion time taken by the two swimmers to both arrive at goals. As shown in Fig. 6(a), the total deviation χ increases with the allowable deviation range ρ, proving the efficacy of the limiter. However, χ doesn't go to zero with ρ because swimmers zigzag towards their goals and swimmers drift every time they turn. On the other end of the curve, χ doesn't increase infinitely with ρ, since the deviations of two swimmers are limited by the controller even without the deviation limiter. The effect of ρ on the time t is more complicated. In general, the swimmers need more time when the allowable deviation range ρ is smaller, as a result of more turns required. However, the time used by making turns is only one part of the total time consumed, and a large amount of time will be taken if a relatively large drifting happens. Therefore, t is less sensitive to ρ and has a relative large standard deviation than χ.

VI. Conclusions

This paper studies the problem of independently controlling two swimmers using a single magnetic field. Two swimmers with net magnetic moments that point in different directions can be controlled to achieve an arbitrary velocity ratio. Based on this, independent positioning of two swimmers is achieved using two computer vision-based feedback controllers: Type I Sequential Controller and Type II Parallel Controller. Type I Sequential Controller manipulates swimmers to move towards their goals one after another, while Type II Parallel Controller moves both swimmers to zigzag towards their goals simultaneously. Two swimmers were controlled to follow a series of goal points defined along the letters "UT", which demonstrate the efficacies and characteristics of the two controllers. Swimmers under the control of Type I Sequential Controller do not deviate much from straight lines, while the deviations of swimmers with Type II Parallel Controller go up and down whilst swimmers move towards their goals. A deviation limiter to restrain the deviations of swimmers with Type II Parallel Controller is implemented for path following tasks, and is characterized with respect to total deviation and path completion time.

This paper only explores the problem of independently controlling two swimmers. For more swimmers, the proposed method does not apply directly, limited by the fact that the heading difference between two swimmers' net magnetic moments is fixed. In our experiments, a large distance is kept between the two swimmers, such that the local interaction between swimmers is negligible. Some experimental results suggest that the behavior of swimmers with strong local interactions can still be modulated. Future research will investigate the problem of manipulating swimmers in close proximity with each other, and completing useful tasks using a team of swimmers.

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