3D Propulsions of Rod-Shaped Micropropellers

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Untethered, magnetically driven microrobots have great potential in practical applications such as minimally invasive surgery. Microrods, also known as "nanowires," are the most commonly used type of structure for microrobots due to the easy fabrication and promising functions. Driven by a uniform rotating magnetic field, microrods can perform a 2D movement with the assistance of a boundary surface, which severely limits the application of microrods in 3D spaces. Herein, an asymmetric structural design is proposed to construct rod-shaped micropropellers that can achieve a surface-free 3D propulsion. A theoretical model is formulated based on resistive force theory to investigate the dynamics of micropropellers. It is theoretically demonstrated and experimentally verified that the magnetic micropropeller can realize not only a 3D propulsion, but also multimodal locomotion to adapt to the environment. The work provides guidance for the design and optimization of autonomous micropropellers.

1. Introduction

Magnetic microrobots have the potential to be controlled remotely and accurately by magnetic fields to move in small confined spaces, e.g., blood vessels, without harm to living organisms. Thus, they have received extensive attention in recent years for their promising applications in biomedical engineering, such as minimally invasive surgery, targeted drug/cell delivery, and in situ sensing. Due to the small feature size (a few nanometers to a few hundred micrometers), microrobots usually work in a low Reynolds number (Re) fluid environment, where the viscous force dominates rather than the inertial force. In this case, a symmetry breaking, including structural asymmetry, actuation asymmetry, and flow asymmetry, is required to avoid a reciprocal motion and achieve a net displacement. For example, driven by a rotating magnetic field, helices and randomly shaped aggregates deploy structural asymmetry to move effectively, and microrods and self-assembled microrobotic linear chains achieve motion through flow asymmetry assisted by a boundary surface, and planar V-shaped structures realize propulsion through the asymmetry codetermined by shape and dipole moment. Flexible or soft microrobots use structural deformation to overcome symmetry and achieve excellent propulsion performance.

1D rigid rod-shaped microrobots were extensively investigated and most widely used because of their easy fabrication and simple theoretical modeling. Driven by a uniform rotating magnetic field, microrods have been used to trap and manipulate microscale objects in fluids through vortexes created by their rotation to stir tiny-volume aqueous fluids in a controlled manner and to form programmable intelligent swarms. In these cases, however, most of the magnetic microrods can only achieve near-surface locomotion. Such surface-assisted 2D motions significantly limit the potential working space that the microrods can reach, thus impeding application scenarios. In addition, some rough surfaces, especially the ones whose surface topology suddenly changes, such as grooved terrains, are also easy to stick and stop the microrods, resulting in the microrods being out of control.

Surface-free 3D motion is of great significance for many practical applications, such as detoxification, drug delivery, microscale agitation, and environmental remediation. It has been proven that helical microswimmers and some planar microstructures can achieve 3D propulsion effectively. Compared with microrods, however, they require higher costs and are more difficult to mass produce due to the complex structures. Furthermore, these rigid microswimmers are normally not capable of morphing shapes or changing propulsion modes to adapt to dynamic environments and complex situations. Therefore, to realize the 3D propulsions of rigid microrods with multiple modes is eminently preferable.

Herein, we present a 3D propulsion mechanism for microrods in the bulk fluid by introducing some degree of structural asymmetry. Using resistive force theory, we calculated the viscous drag forces and formulated the dynamics of the propelled microrods. Theoretical analyses show that the asymmetric rod-shaped micropropellers can realize not only surface-free...
propulsions but also controllable multimodal locomotion. These micropropellers have an in-plane rotating “spinning” mode that can gain a high propulsion speed and an out-of-plane biconical rotating “precession” mode enabling the micropropeller to pass through narrow channels due to a smaller rotation radius. Importantly, the propulsion mechanism and multimodal propulsion property are verified experimentally. The ability of multimodal 3D propulsion can greatly improve the environmental adaptability of the microrods, and make them more practical in complex environments for many applications, which will provide theoretical guidance for the design and optimization of microrods and pave the way for their broad application.

2. Results

2.1. Design of Structural Asymmetry for 3D Propulsion

Driven by a uniform rotating magnetic field, the resultant force exerted by the magnetic field is zero. To achieve 3D locomotion, it is required that the force exerted by the fluid along the rotation axis on the microstructures not be zero. The geometry of the microstructure is an important factor that affects the fluid force on it during its rotation. Compared with microrods, current structures that can achieve 3D propulsion, such as helices, randomly generated aggregates, and even planar structures, have a greater degree of structural asymmetry. This asymmetrical characteristic enables the microstructure to receive uncompensated fluid forces along the rotation axis so that its 3D movement can be achieved. However, for a highly symmetrical microrod, in the case of torque equilibrium, no matter the posture it rotates in, the forces will be canceled out and cannot produce effective displacement but resistive torque. Thus, we could infer that the introduction of structural asymmetry into the microrod could be a feasible way to realize its 3D propulsion.

Therefore, a generalized model of the asymmetric microrod is first established to conduct force analysis (Figure 1A). Assuming that the microrod is rotating synchronously with angular velocity \( \omega \) under a uniform magnetic field \( H \) with magnetic torque \( T_m \) in a still incompressible Newtonian fluid, inducing the flow of the surrounding fluid, and is subjected to fluid resistive force \( F_e \) and torque \( T_e \). For \( 2L \) is the total length of the rod. Figure 1B shows an infinitesimal element with length \( dL \) and characteristic size \( R \) at position \( r \) of the microrod; the local velocity is \( v \). The fluid force and torque applied to the infinitesimal element are \( dF_{\text{fl}} \) and \( dT_{\text{fl}} \), \( \rho \), \( \eta \), \( u \), and \( \theta \) are the density, viscosity, pressure, and velocity of the fluid, respectively.

As the source of the lift force is the fluid force, this section first analyzes the influence of the asymmetry on the fluid force exerted on the microrod to give a preliminary asymmetric structural design.

Taking microswimmers in water as an example, the density and viscosity of deionized water (DI water) at room temperature are \( \rho = 0.997 \text{ g cm}^{-3} \) and \( \eta = 8.949 \times 10^{-4} \text{ Pa s} \), respectively; thus, the velocity and characteristic size corresponding to \( \text{Re} = 1 \) satisfies \( vR = \eta/\rho = 8.98 \times 10^{-7} \text{ m s}^{-1} \). That is, for the flow rate of 1 mm s\(^{-1}\), the characteristic size for \( \text{Re} = 1 \) is 898 \( \mu \)m. For the motion of most microorganisms or micro/nanorobots, as the \( R \) and \( v \) are much smaller, the Reynolds number \( \text{Re} = \rho vR/\eta \) is typically around \( 10^{-2} \)–\( 10^{-5} \). When the microrod moves with \( \text{Re} < 1 \) and the rotation/oscillation frequency of the structure is not too high, its inertia forces can be ignored, and the Navier–Stokes equations are reasonably simplified to the linear Stokes equations. According to the linear properties of Stokes equations, the overall flow force on the microrod can be obtained by the linear superposition of cross-sectional elements. Therefore, the force analysis of an arbitrary asymmetric cross-sectional element is to be conducted. As shown in Figure 1B, the fluid force and torque applied to the infinitesimal element with length \( dL \) are \( dF_{\text{fl}} \) and \( dT_{\text{fl}} \); thus, the overall forces and torques on the microrod in Figure 1A can be obtained by integrating the forces and torques on the infinitesimal element as the resultant force \( F_v = \int dF_{\text{fl}} \) and resultant torque \( T_v = \int dT_{\text{fl}} + \int_{2L} (r \times dF_{\text{fl}}) \). Here, we assume that the forces on each infinitesimal element do not interfere with each other.

As for the infinitesimal element, although the forces and torques on it can be obtained by integrating the fluid stress over the geometric boundary, they are related to the element’s cross-sectional shape. According to the previous description, the goal of our structural design is to ensure that there is a fluid force component in the direction perpendicular to the relative fluid velocity, i.e., in the direction of the rotation axis; thus, this component can act as a lift force to realize the 3D propulsion of the microstructure.

To determine the parameters of the structural design, we need to give a specific asymmetric cross-sectional configuration. Here, we take the elliptical segment, a typical asymmetric structure, as an example, to discuss the design of structural parameters. The elliptical segment is shown in Figure 2Ai, where \( R_e, R_t, \) and \( a \) are the long and short half-axes of the ellipse and the cutting depth along the short axis.

According to the linear properties of Stokes equations, we know that the resistance and torque depend on the velocity and angular velocity linearly. Therefore, the resistance force theory (RFT) can be introduced, i.e., using the resistance coefficient to represent the linear relationship between the fluid resistance of the structure and its relative fluid velocity. Then, the force analysis of the asymmetric section (elliptical segment) is shown in Figure 2Aii, where \( \xi_1 \) and \( \xi_2 \) given by the product of the fluid viscosity \( \eta \) and the shape factors \( \xi_i \) (\( i = 1, 2 \)) are resistance coefficients in the two principal axes, \( dF_{\text{lin}} \) and \( dT_{\text{lin}} \) are lift force and torque applied by the fluid respectively, \( \theta \) is the angle between the relative flow velocity \( V_r \) (seen from the frame fixed with the solid section) and the normal direction denoted by \( n \) outside the cutting surface, \( r_c \) represents the distance between the resultant force center \( C_f \) and the elliptical center \( O_e \), and it is worth noting that \( a \neq 0 \) is required to ensure that \( r_c \neq 0 \). The relationship between the two drag coefficients and asymmetric parameters \( a \) and \( R_e \) is simulated and supplemented in Figure S1. Supporting Information.

From the analysis in Figure 2Aii, we can obtain the following relationships

\[
dF_{\text{lin}} = \frac{1}{2} (\xi_1 - \xi_2) \eta V_r \sin 2\theta, \quad dT_{\text{lin}} = r_c \xi_2 \eta V_r \sin \theta
\]

(1)

We can learn from the expression of \( dF_{\text{lin}} \) in Equation (1) that if a net force requires \( 1 \) the shape factors \( \xi_1 \neq \xi_2 \), which is satisfied
as long as the cross-section is not a perfect circle, including the circular segment ($a \neq 0$) and ellipse ($R_2 \neq R_1$) as shown in Figure 2Aii and elliptical segment ($a \neq 0$ and $R_1 \neq R_2$); 2) the inflow angle $\theta$ is not $0^\circ$ or $90^\circ$. Moreover, the maximum lift force is obtained when the angle $\theta$ is $45^\circ$ or $225^\circ$.

The axial local resistive torque for the unrotated element is induced from the asymmetry in the short axis of the elliptical segment and can be expressed as $d\tau_{\text{vs}}$ in Equation (3), from which we can learn that, as $r_2 \neq 0$ (requiring $a \neq 0$) and the angle $\theta$ is not $0^\circ$ or $90^\circ$, there will always be a fluid resistive torque.

Based on this analysis, we propose a structural design of a micropropeller as shown in Figure 2B. The micropropeller is an orthogonal coaxial combination of two identical microrods with cross-sectional shape parameter $a \neq 0$, ensuring that $\xi_1 \neq \xi_2$ and $r_2 \neq 0$ to make it possible that we get the maximum lift force assisted by the balance of the rod’s axial torque. The two angles $\theta_1$ and $\theta_2$ corresponding to $\theta$ in Figure 2Aii satisfy torque balance at $\theta_1 = \theta_2 = 45^\circ$ for the orthogonal (the sum of angles $\theta_1$ and $\theta_2$ is $90^\circ$) combination, corresponding to the maximum lift force.

Furthermore, the effective 3D propulsion of micropropeller, as well as the propulsion performance, also depend on micropropeller’s stable rotating state under torque balance condition. The requirements for the final design parameters of the micropropeller, including magnetization parameters, can be determined after the corresponding stable motion state is given by comprehensively considering the dynamic characteristics. Therefore, after the proposal of the aforementioned structural design, it is also necessary to further analyze the micropropeller’s dynamic characteristics under the coupling action of the flow field and the magnetic field, which is going to be conducted in the following section.

2.2. Propulsion Modes of the Asymmetric Micropropeller

Before studying the rotating dynamics of the proposed asymmetric micropropeller, some assumptions are to be made first. 1) The micropropeller is in an unbounded and originally static flow field; 2) the viscous force from the flow field and torque from the magnetic field dominate the propulsion of the...
micropropeller, and other forces such as gravity are ignored; 3) the resistance coefficients of each infinitesimal element are considered to be consistent along the rod's long axis and the forces do not interfere with each other.

As shown in Figure 3A, two sets of coordinate frames are used in our analyses: the global coordinate system (Gcs-XYZ) fixed in space and the local coordinate system (Lcs-x_1y_1z_1) affixed to the rod's body. For convenience, the two coordinates have the same origin, which is set at the center of the ellipse where the two cylindrical components intersect. Three angles α, β, and γ following Euler's convention (in the standard "313" parametrization) are used to describe the orientation of the micropropeller. Thus, the transformation relationship between the two coordinates can be represented by the rotation matrix \( \mathbf{R}^{(3)} \) parametrized by α, β, and γ, and any vector \( \mathbf{p}^{\text{Gcs}} \) in the global coordinate system can be converted to the local coordinate system as \( \mathbf{p}^{\text{Lcs}} = \mathbf{R} \cdot \mathbf{p}^{\text{Gcs}} \).

As shown in Figure 3B, the uniform magnetic field can be expressed in the global coordinate system Gcs as \( \mathbf{H}^{\text{Gcs}} = H_0 (\cos \theta, \sin \phi, 0) \), where \( H_0 \) and \( \omega \) are the magnetic field amplitude and angular frequency, respectively. The magnetic moment fixed on the object is given in Lcs (Figure 3C) as \( \mathbf{m}^{\text{Lcs}} = m_0 (\cos \theta \cos \phi, \cos \theta \sin \phi, \sin \theta) \), where \( m_0 \) is the magnitude of the magnetic moment, and \( \theta \) and \( \phi \) are the two azimuths of the magnetic polarization (Figure 3C). The force exerted by a uniform magnetic field is 0, and the motion of the magnetized micropropeller is only driven by the magnetic torque. The magnetic torque \( \mathbf{T}_m^{\text{Lcs}} \) on the micropropeller in the local coordinate system Lcs can be given by the following formula

\[
\mathbf{T}_m^{\text{Lcs}} = \mathbf{m}^{\text{Lcs}} \times (\mathbf{R} \cdot \mathbf{H}^{\text{Gcs}})
\]

The fluid forces and torques on the asymmetric micropropeller are calculated using the resistive force theory (RFT). Assuming that the translational and rotational velocities of the structure in the global coordinate system Gcs (take the origin as a reference) are \( \mathbf{V}_0 \) and \( \Omega \), respectively, then the velocity of the infinitesimal element at position \( \mathbf{r} \) in the local coordinate system Lcs is \( \mathbf{v}^{\text{Lcs}} = \mathbf{R} \cdot (\Omega \times (\mathbf{r}^2 + \mathbf{r})) + \mathbf{V}_0 \). The infinitesimal element with length \( dl \) at the coordinate \( \mathbf{r} = (0, 0, l) \) is subjected to the fluid force \( \mathbf{dF}_w^{\text{Lcs}} = -k \mathbf{v}^{\text{Lcs}} dl \) in the local coordinate system Lcs, where \( le(-L, L), 2L \) is the total length of the rod, and \( k \) is the resistance coefficient matrix for the rod per unit length. The resistance coefficient matrix \( k \) corresponding to the two orthogonal components can be expressed as \( k = k_{\parallel} = \text{diag}(\eta_2, \eta_2) \) at \( le(-L, L) \) and \( k = k_{\perp} = \text{diag}(\eta_1, \eta_1) \) at \( le(0, L) \). Here, \( \eta_2 \) and \( \eta_2 \) are the resistance coefficients along the short and long axis (see Figure 2Aii, shape factors \( \xi_2 > \xi_2 \) ), respectively. The torque of fluid exerted on the micropropeller at \( \mathbf{r} = (0, 0, l) \) is \( \mathbf{dT}_w^{\text{Lcs}} = r \times \mathbf{dF}_w^{\text{Lcs}} + \mathbf{dT}_{w-\text{axis}}^{\text{Lcs}} \), where \( \mathbf{dT}_{w-\text{axis}}^{\text{Lcs}} = (0, 0, dT_{z1})^T \) is the resulting torque exerted on the centroid of the original elliptical shape, containing two parts that come from the micropropeller’s rotation and translation respectively as \( dT_{z1} = -k_w \omega_2 d l - k_v \omega_2 d l \) at \( le(0, L) \) and \( dT_{z1} = -k_w \omega_2 d l + k_v \omega_2 d l \) at \( le(-L, 0) \). (See Section S1 and Figure S2, Supporting Information for details). \( k_w \) and \( k_v \) are the rotational and translational coefficients, respectively, where \( r_c \) is the distance between the resultant force center \( \Omega \) and the elliptical center \( O_c \) as mentioned in the previous section, demanding \( a \neq 0 \) for \( r_c \neq 0 \).

The aforementioned forces and torques satisfy the following force equilibrium conditions

\[
\int d\mathbf{F}_w^{\text{Lcs}} = 0, \quad \int \mathbf{T}_m^{\text{Lcs}} + \int d\mathbf{T}_{w}^{\text{Lcs}} = 0
\]

Using all the aforementioned relations and sorting them out, the following governing equations can be obtained from Equation (3)

Figure 3. Theoretical model. A) The global (Gcs-XYZ) and local (Lcs-x_1y_1z_1) coordinate frames and the corresponding Euler angles α, β, and γ. B, C) The definitions of the magnetic field \( \mathbf{H} \) (in Gcs-XYZ) and the magnetization \( \mathbf{m} \) (in Lcs-x_1y_1z_1) of the micropropeller, respectively.
To solve the equations, the rotating state of the micropropeller can be divided into two catalogs by different conditions (see Section S2, Supporting Information, for details). We have obtained the following solutions. After further solving the equation under the aforementioned conditions, we find that the analytical solution can be obtained in three cases: 1) \( \theta = 0 \), \( \Phi = \theta = \pi/2 \); 2) \( \theta = 0 \), \( \Phi = \pi/4 \); and 3) \( \theta = 0 \), \( \Phi = \pi/2 \).

In this article, we mainly consider the case of analytical solutions. After further solving the equation under the five aforementioned conditions (see Section S2, Supporting Information, for details), we find that the analytical solution can be obtained in three cases: 1) \( \theta = 0 \), \( \Phi = \pi/4 \); and 3) \( \theta = 0 \), \( \Phi = \pi/2 \).

In the case of \( \Phi = -\pi/4 \), the Euler angles and velocity in the stable state can be divided into two catalogs by defining a critical driving frequency as (stability analysis is shown in Section S2 and Figure S3, Supporting Information)

\[
\omega_1 = \frac{m_0 H_0}{q_1 \eta} \sin \theta
\]  

\( \beta = \frac{\pi}{2} \), \( V_{0z} = \frac{\xi_1 - \xi_2}{\xi_1 + \xi_2} \omega \) (at \( \omega \leq \omega_1 \))  

(7)

From this equation, we can conclude that the propulsion speed in the spinning mode is independent of the viscosity \( \eta \) of the fluid.

The other two Euler angles are \( \alpha = o t - \alpha \), \( \varphi_1 = (\xi_1^2 + 4 \xi_2 \xi_3 + \xi_3^2) L^2 / (12 \xi_1 + 12 \xi_2) \), \( \varphi_2 = L^2 \xi_2 \xi_3 / (\xi_1 + \xi_2) \), \( s_\theta = c_\alpha \), \( c_\theta = \sin \alpha \), and \( \alpha, \beta, \gamma \) do not change with time, i.e.

\[
\alpha = \omega t - \alpha, \beta = 0, \gamma = 0
\]  

(5)

The steady-state equation \( \beta = 0 \) can be valid at \( c_\beta \xi_3 + c_\theta \xi_3 \Phi = 0 \) or \( s_\theta = 0 \), and the former can be further divided into four cases: 1) \( \beta = \pi/2, \gamma + \Phi = 0 \); 2) \( \beta = \pi/2, \gamma = \pi/2 \); 3) \( \gamma = 0, \beta = 0 \); or 4) \( \gamma = 0, \beta = \pi/2 \).

In this article, we mainly consider the case of analytical solutions. After further solving the equation under the five aforementioned conditions (see Section S2, Supporting Information, for details), we find that the analytical solution can be obtained in three cases: 1) \( \theta = 0 \), \( \Phi = -\pi/4 \); and 3) \( \theta = 0 \), \( \Phi = \pi/2 \).

When \( \theta = 0 \), \( V_{0z} = 0 \) and no net translation is produced. Therefore, the case of \( \theta = 0 \) is not considered.

In the case of \( \Phi = -\pi/4 \), the Euler angles and velocity in the stable state can be divided into two catalogs by defining a critical driving frequency as (stability analysis is shown in Section S2 and Figure S3, Supporting Information)

\[
\omega_1 = \frac{m_0 H_0}{q_1 \eta} \sin \theta
\]  

(6)

From the expression of \( \omega_1 \), we learn that for a micropropeller with a specific sectional shape \( q_1 \) is constant) and specific magnetization angle \( \theta \), a higher critical frequency \( \omega_1 \) is obtained at lower viscosity \( \eta \) and higher magnetization intensity \( m_0 \) and external magnetic field strength \( H_0 \).

When the driving frequency \( \omega \) is less than or equal to \( \omega_1 \), we have the spinning propulsion state denoted by precession angle \( \beta \) and speed \( V_{0z} \) as
to a smaller radius of rotation adapted to narrower space. Thus, the motion mode and velocity of the micropropeller can be predicted and regulated to meet specific requirements of propulsion.

The critical and step-out frequency versus magnetization angle $\theta$ are plotted as the solid lines in Figure 4A, which divide the rotating states into three categories: 1) driving frequency below $\omega_1$, corresponding to the spinning propulsion mode, where the propulsion speed is linearly increased with the driving frequency and the maximum speed can be obtained; 2) driving frequency between $\omega_1$ and $\omega_{\text{step-out}}$, corresponding to the precession mode, where the micropropeller has a smaller radius of gyration, enabling the micropropeller to enter a narrower space; and 3) driving frequency above $\omega_{\text{step-out}}$, corresponding to the stepout mode, which is the state of nonsynchronous rotation, thus not being considered further in this article. The mode-changing ability makes the designed micropropeller more flexible in motion and more adaptable to complex terrain.

In the case of $\theta = \pi/2$, $\beta = \pi/2$ is the only solution because the critical frequency is approximately equal to the step-out frequency (see Section S2, Supporting Information), which means that the corresponding rotating state is only the in-plane spinning mode, and the expression of the propulsion speed is $V_{\text{prop}} = (\xi_1 - \xi_2)\omega_0/(2\xi_1 + 2\xi_2)$. More details can be seen in Section S2, Supporting Information.

To summarize, in this section, we have shown that the 3D propulsion of the designed rod-shaped micropropeller requires that the magnetization angle $\theta \neq 0$ (nonzero velocity) and the cross-sectional shape of an elliptical or circular segment with $a \neq 0$ to achieve steadily controlled 3D propulsion. Furthermore, the designed micropropeller has two effective propulsion modes (spinning mode and precession mode) switchable by the frequency of the driving magnetic field in the condition of the magnetization angle $\theta \neq \pi/2$.

In the following section, we experimentally verify the 3D propulsion ability and dynamics of the asymmetry-structured rod-shaped micropropeller.

### 2.3. Experimental Verification

The experimental verification includes two aspects: one is to verify the implementation of the effective 3D propulsions of the asymmetric micropropeller in the bulk fluid away from the surface; the other is to verify the stable propulsion states of the micropropeller predicted by Equation (7) and (8). Here, a polymeric asymmetric micropropeller was printed through 3D direct laser writing and then coated with nickel (Ni) and titanium (Ti).

Figure 5A shows the overall fabrication procedure of the asymmetric micropropeller, including the prototyping of the micropropeller fabricated by two-photon polymerization (TPP)-based 3D direct laser writing, and the deposition of nickel (Ni) and titanium (Ti) layers for magnetic and biocompatible properties, respectively. Figure 5B i, ii are the designed prototype and scanning electron microscopy (SEM) image of the fabricated asymmetric micropropeller, respectively. As the motion performance of the micropropellers is closely related to their magnetic properties, the nickel (Ni) metal layer on the surface of the micropropellers was further characterized by the energy-discharging X-ray detector, as shown in Figure 5Biii, which indicates the successful sputtering of the metal nickel. Then the magnetic properties of the micropropellers were tested, and the hysteresis loop diagram is shown in Figure 5Biv, indicating that the micropropellers have soft magnetism. It is noted that although the micropropeller proposed in this work still needs the same fabrication process used by most helical microswimmers, it requires less printing time due to the smaller fabrication height than helical microswimmers.

In Figure 5C, the axis of the rotating magnetic field was set in the vertical direction. An upper mounted microscope was used to record the micropropeller’s locomotion, focusing on the plane of the substrate where the micropropeller initially rest. Figure 5C i-vi are the time-lapse images of the rotating micropropeller driven by a magnetic field of 10 mT, with the micropropeller gradually moving upward away from the focusing plane (substrate). In Figure 5Cvi, the micropropeller has left the focus plane of the microscope, which indicates that the asymmetric micropropeller has successfully taken off from the surface of the bottom boundary and achieves 3D propulsion at the frequency of 4 Hz. After taking off from the substrate, the controlled propulsion trajectory of the micropropeller with the square shape was demonstrated (refer to Figure S4 and Movie S3, Supporting Information), where the axis of rotation of the magnetic field was inclined upward to an angle of 55° with the bottom surface (horizontal plane) and the driving frequency is 6 Hz.

Figure 5D shows time-lapse images of the micropropeller in spinning and precession mode, respectively (taken from Movie S2, Supporting Information, top view). The critical frequency of the micropropeller is 12 Hz, above which the propulsion mode of the micropropeller changes from spinning mode to precession.
mode, with a smaller radius of rotation. Other realization of the 3D propulsion of the micropropeller can be found in Figure S5 and S6 (taken from Movie S1) and Movie S3, Supporting Information.

Figure 6A shows the cosine value of the precession angle $\beta$ of the micropropeller as a function of dimensionless frequency $\omega/\omega_1$, where $\omega_1$ (rad·s$^{-1}$) is the critical angular frequency, $f_1 = \omega_1/2\pi$. The solid line is the theoretical curve predicted by the expression of $\beta$ in Equation (7) and (8), the square points are the experimental points of micropropellers with different critical frequencies $f_1$. The theoretical prediction (solid lines) fits the experimental data (scattered points) well. The insets (i), (ii), and (iii) are the experimental rotation states of the micropropeller driven by a magnetic field with frequencies of 1 Hz (spinning), 8 Hz (precession), and 19 Hz (precession), respectively. In Movie S2, Supporting Information, the motion mode changes from spinning mode to precession mode when the rotation frequency of the magnetic field is over 12 Hz. Reduced rotation radius of the micropropeller is presented as the increased rotation frequency in precession mode, which shows the adaptability of the micropropeller to the environment.

Figure 6B plots the relationship between the propulsion velocity of the micropropeller and the frequency of the driving magnetic field, where the solid line predicted by the theoretical
Figure 6. Experimental verification of the propulsion modes and speed of the micropropeller. A) Cosine value of precession angle $\beta$ plots as a function of $\omega/\omega_1$, where $\omega$ (rad s$^{-1}$) is the critical angular frequency, $f_i = \omega_i/2\pi$. The solid line is the theoretical curve predicted by the expression of $\beta$ in Equation (7) and (8); the square points are experimental points with different critical frequencies $f_i$ as denoted in the figure. The insets (i), (ii), and (iii) show the rotation attitude of a micropropeller driven by a magnetic field with a frequency of 1 Hz (spinning), 8 Hz (precession), and 19 Hz (precession), respectively. Scale bar: 20 $\mu$m. B) Propulsion velocity of the asymmetric micropropeller under varying driving frequencies of the magnetic field at 10 mT. The solid line is the theoretical prediction from Equation (7) and (8) and the scattered points are experimental results. The inset is the micropropeller under a static (0 Hz) uniform magnetic field, from which we obtained that the magnetization angle of the micropropeller $\theta = 50.28^\circ$ (scale bar: 20 $\mu$m). Error bars denote standard errors estimated from position uncertainty in image analysis and observation time used to measure velocity.

Equation (7) and (8) fits the experimental points well. The results show that the propulsion velocity increases linearly with frequency in the spinning regime below $\omega_1$ (7 Hz in the experiment) and then decreases gradually. The maximum propulsion speed ($44 \pm 7.9 \mu$m s$^{-1}$) of the rod-shaped micropropeller is obtained at the critical frequency $\omega_1$ (7 Hz in the experiment), above which the mode of propulsion transforms from spinning to precession. The inset in Figure 6B shows the orientation of the micropropeller under a static magnetic field, in which case the direction of magnetization of the micropropeller is the same as the direction of the external magnetic field, from which we measured the magnetization angle of the micropropeller as $\theta = 50.28^\circ$.

Considering the propulsion speed of microorganisms and several typical artificial microstructures, we can learn that the propulsion speed of the presented micropropeller ($44 \pm 7.9 \mu$m s$^{-1}$) is comparable (swimming speed 18 $\mu$m s$^{-1}$ for the helix proposed in Zhang et al.,$^{25}$ 22 $\mu$m s$^{-1}$ for the flexible artificial flagellum in Dreyfus et al.,$^{26}$ and 30 $\mu$m s$^{-1}$ for Escherichia coli$^{27}$) and optimistic to be used in practical applications. A higher dimensional or dimensionless propulsion speed can be obtained through optimizing the structure according to the expression of the velocity $V_{0z_{-\max}}$ in Equation (9) presented in Section 2.

Further experiments were conducted in a 1:1 volume ratio mixture of pure deionized (DI) water and glycerol with greater viscosity to investigate the effect of viscosity on the movement of the micropropeller. The results show that the propulsion speed in the more viscous mixture is close to that in pure DI water when the rotating frequency $\omega$ is lower than the critical frequency $\omega_1$, but decays more rapidly when $\omega > \omega_1$ (see Figure S7, Supporting Information, for details).

Finally, we also numerically supplement the flow field diagram induced by the micropropeller rotating about a fixed axis (z-axis) with the frequency of 20 Hz at angle $\beta = 90^\circ$, and the lift force versus varying precession angle $\beta$ with $\gamma$ kept at a constant angle of 45° (see Figure S8, Supporting Information).

3. Conclusion

Due to the simplicity of the structure, microrods are most commonly used in practical applications, and it is of great significance to enable the propulsion of a microrod in three dimensions free of the surface to extend its application scene and improve its efficiency. Inspired by the asymmetric properties of natural and artificial propellers, in this article, an asymmetric factor was introduced into a originally highly symmetric microrod to design a rod-shaped micropropeller and realize its effective surface-free 3D propulsion in a bulk fluid under a rotating magnetic field. The propulsion mechanism of the asymmetric micropropeller was investigated theoretically and verified experimentally. The asymmetric micropropeller can achieve not only effective 3D motion but also two stable propulsion states to improve its adaptability to complex environments. This article can be used as a guide for the design of micropropellers with 3D propulsion ability and paves the way for the wide applications of microrods in complex environments.

4. Experimental Section

Fabrication of the Micropropellers: The rod-shaped micropropellers were built by AutoCAD 2017 and were fabricated through the 3D direct laser writing (DLW) method on a Nanoscribe Photonic Professional GT (Nanoscribe GmbH, Germany). Before printing, a droplet of IP-L photoresist (from Nanoscribe GmbH, Germany) was first coated on a square borosilicate glass substrate ($22 \times 22 \times 0.15$ mm, Thermo Fisher Scientific, USA). Then the asymmetrically designed microrods were written in the photoresist using the Nanoscribe Photonic Professional GT with the oil-immersion 63 x objective (NA = 1.4, from Zeiss “NA” denotes
Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

This work was funded by the National Natural Science Foundation of China (grants nos. 91848201, 11988102, 11521202, 11872004, 11802004, 11702003, and 62073002) and Beijing Natural Science Foundation under grants no. L172002. The authors also greatly appreciate Dr. Yahui Xue’s useful discussion and Jiajia Liao’s help in sample preparation.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

asymmetric design, magnetic actuation, rod-shaped micropropellers, 3D propulsions

Received: May 6, 2021
Revised: July 26, 2021
Published online: August 30, 2021

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