Self-Propulsion and Shear Flow Align Active Particles in Nozzles and Channels

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Active particles consume energy stored in the environment and convert it into mechanical motion. Many potential applications of these systems involve their flowing, extrusion, and deposition through channels and nozzles, such as targeted drug delivery and out-of-equilibrium self-assembly. However, understanding their fundamental interactions with flow and boundaries remains incomplete. Herein, experimental and theoretical studies of hydrogen peroxide (H$_2$O$_2$) powered self-propelled gold–platinum nanorods in parallel channels and nozzles are conducted. The behaviors of active (self-propelled) and passive rods are systematically compared. It is found that most active rods self-align with the flow streamlines in areas with high shear and exhibit rheotaxis (swimming against the flow). In contrast, passive rods continue moving unaffected until the flow rate is very high, at which point they also start showing some alignment. The experimental results are rationalized by computational modeling delineating activity and rod-flow interactions. The obtained results provide insight into the manipulation and control of active particle flow and extrusion in complex geometries.

1. Introduction

Active particles are capable of self-propelling by consuming energy from the environment.[1] The particles may be living, such as bacteria, or synthetic, such as bimetallic rods or spherical Janus particles. Due to persistent energy input, active materials are examples of out-of-equilibrium systems. They exhibit variety of intriguing phenomena such as the onset of collective behavior,[2–3] reduction of effective viscosity,[4–6] extraction of useful energy,[7–9] and enhanced mixing.[10–12]

Typically, active microswimmers show a preferred orientation which determines the self-propulsion direction. Distribution of active particle orientation may have a significant impact on the macroscopic properties of the active material. It was shown in refs.[13–15] that reduction of effective viscosity in the suspension of active microswimmers, exemplified by bacteria, may be explained by a specific form of orientational distribution with respect to the background shear flow. In refs.[16,17] authors showed how the orientation of active microswimmers in the background shear flow leads to the formation of depletion regions, where particles’ number density is significantly lower than the average value.

Chemically-driven synthetic microswimmers, mimicking motility of living micro-organisms, were first introduced by Paxton et al.[18] Since then the repertoire of synthetic microswimmers, as well as mechanisms which can be used to activate their self-propulsion, have significantly expanded.[19] The importance of synthetic microswimmers is twofold. On the one hand, their development leads to a variety of potential applications, for example in medicine[19,20] and materials science.[21] On the other hand, their study sheds new light on fundamental motility mechanisms and biological self-organization.
Chemically-driven bimetallic nanorods represent a popular design of the self-propelled active particles.[18] This type of synthetic swimmers is usually similar in shape and size to Bacillus bacteria: rod-like shape, a few micrometers in length, and a few hundred nanometers in width. They are composed of two or more metals on which catalytic decomposition of H₂O₂ occurs, generating an ion flow that propels the particles in their longitudinal direction. Through this mechanism of self-propulsion, these particles exhibit exciting behaviors mimicking that of its biological counterparts such as the ability to swim across flow streamlines, upstream migration, and wall accumulation.[22–30] In the absence of H₂O₂, the same particles are passive because no chemical reaction occurs.

In this article, we investigate the behavior of active particles in the presence of confined flows and compare it with the behavior of passive particles. We find that while most active rods self-align with the flow streamlines in areas with high shear and exhibit rheotaxis (swimming against the flow), passive rods continue moving unaffected until the flow rate is very high. Our experimental results are supported by a computational model of simplified rod-flow interactions.

2. Experimental Results

The particles, both active and passive, have a cylindrical shape and are composed of gold and platinum halves longitudinally opposed, as shown in Figure 1b. A total length and diameter of approximately 2 μm and 400–500 nm, respectively. Active nanorods self-propel with the platinum side pointing forward due to the catalytic decomposition of H₂O₂.[18,31]

Catalytic decomposition of H₂O₂ causes asymmetric charge distribution around the active particles. The balance of the electrostatic, hydrodynamic, and gravitational forces results in the nanorods having a tilt angle $\phi$ relative to the bottom. In this configuration, the platinum side lays at the bottom and the gold side above. Passive particles, in contrast, generally lay flat at the bottom as no H₂O₂ is present. In the absence of flow, this configuration is only altered by the inherent (and rather insignificant) rotational diffusion of the nanorods. To extract information about the flow alignment, we measure the angle $\theta$ between the nanorods and the longitudinal orientation of the microchannel, Figure 1b.

To better understand the effects of confined fluid flow on the particles, we pump a suspension of nanorods through a polydimethylsiloxane (PDMS) microchannel consisting of two sections with parallel walls separated by a distance of 100 and 10 μm, joined together by a nozzle of length 100 μm, Figure 1a. The height of the channel is 50 μm. Active particles are suspended in a solution of 15% H₂O₂ to ensure maximum self-propulsion speed,[18] whereas passive particles flow in water. Due to their high density, the bimetallic nanorods sediment rapidly to the bottom of the channel upon entrance. We varied the flow rate with a microfluidic pump at rates ranging from 0.5 to 10 μL h⁻¹. These flow rates correspond to a mean flow speed in the channel in the range of 27.5 to 550 μm s⁻¹.

No-slip boundary condition at all of the interior surfaces of the microchannel would force the flow velocity to vanish at the walls and increase toward the center of the channel. Figure 1c shows the shear rate in a line perpendicular to the length of the channel and at a height of 2 μm of the bottom. We observe that because of the

![Figure 1. a) Nozzle section of a channel with nanorods deposited at the bottom. Color bar: Log(Shear Rate) at the walls, COMSOL Multiphysics simulation. b) 3D representation of a bimetallic nanorod with orientation angles $\theta$ and $\psi$, horizontal and vertical angles respectively. c) Shear rate and its components in a line perpendicular to the length of the channel and at 2 μm from the bottom. $y = 0$ μm at the wall and $y = 50$ μm at the center of the channel. Mean flow speed 550 μm s⁻¹ (flow rate 10 μL h⁻¹).](image-url)
shear in the z-component, an active particle with tilt angle $\phi$ different from zero is exposed to different flow velocities at its two ends. The flow velocity is almost zero at the bottom and higher at the top. The change in flow velocities translates to the particle feeling a differential torque from the different hydrodynamic drag forces, resulting in the particle being aligned with the streamlines of the flow by pivoting around the lower end, as a weather vane. A similar effect is observed in the $y$-direction if a particle is not perfectly aligned with the flow streamlines, has an angle $\theta$ different from zero, and is not exactly at the center of the channel. In this case, the flow increases velocity toward the center. The plots in Figure 1c show that $z$-component of the shear is much stronger than $y$-component away from the lateral walls, where $y$-component dominates. This phenomenon effectively creates two zones where alignment is possible but it is produced by different components of the shear flow.

We compare the behavior of active and passive particles in the channel section with parallel walls (channel) and the section with tapered walls (nozzle). At the microchannel inlet, the laminar flow is established within a distance of approximately 100 $\mu$m, equal to the width of the channel in that section. After this point, the velocity profile does not change along the parallel segment until it reaches the nozzle (700 $\mu$m downstream). The observation area for the experiments starts 200 $\mu$m before the nozzle, giving the particles about 400 $\mu$m to reach a steady-state before the first observation in the parallel channel section. Deducing from the observed rapid changes in alignment between the four different observation sections spaced 35 $\mu$m apart, the length of the inlet section is sufficient to achieve a steady state. We did not see changes in alignment along the 200 $\mu$m section of the parallel channel in our observation zone.

In the channel section, 2D histograms of horizontal angle distributions versus the $y$-coordinate, Figure 2 first column, show that for a slow flow rate of 10 $\mu$L h$^{-1}$ (55 $\mu$m s$^{-1}$) the angle distribution is almost homogeneous. At this shear regime, passive particles remain randomly oriented and active ones can swim in any direction without noticeable alignment effects. With an increase in the mean flow speed to 165 $\mu$m s$^{-1}$, we observe active particles rapidly aligning horizontally with the flow streamlines but passive particles need a much higher mean flow speed of 550 $\mu$m s$^{-1}$ to show any noticeable alignment. We deduce that the differences in magnitude between the shear rate in $y$ and $z$-directions are responsible for this difference in alignment. This is because passive particles lay flat and are only affected by the $z$-component of the shear which increases much slower with the flow compared with the $z$-component aligning the active nanorods.

The nozzle section accelerates the flow velocity by reducing the cross-section of the channel. To better understand its effect, we divided it into three subsections and plotted separate 2D histograms, Figure 2 second to fourth columns. The distance to the wall was normalized on the nozzle width to eliminate ambiguity due to the nozzle geometry. Here we observe how all particles gradually appear more aligned with the flow, as it is increased externally or due to the reduction of the nozzle cross-section. As the cross-section becomes smaller, the difference in flow velocity between the wall and the center increases. This increase in shear enhances the alignment in the center of the nozzle. The observed apparent focusing of passive particles, i.e., accumulation near the center of the channel, is a statistical representation of the difference in alignment between the particles at the wall and the center. We do not observe noticeable active particles focusing as in ref. [29]. This is mainly due to the rotational diffusion of active particles, which is for our experimental conditions ($D_r = 0.86$ s$^{-1}$) compared to the flow shear rate; see Supporting Information. As self-propulsion permits active particles to swim across the channel, we observe that closer to the walls of the nozzle, their orientation angle is not zero, but close to 24.4°, which is the angle of the nozzle walls with respect to the center-line of the channel.

Closer to the walls, the flow velocity is small, and the shear ensures that swimming particles align anti-parallel to the flow. These conditions allow swimming upstream, a movement referred to as positive rheotaxis.$^{[30]}$ Due to rotational diffusion, active particles close to the wall also reorient and get injected into the stream, generating looping trajectories. These two observed behaviors are shown in Figure 3 trajectories 7 and 8. One notices that due to particles swimming with the platinum side forward, which is lower in the tilted configuration, the stable alignment orientation for active particles is always anti-parallel to the flow. It means that shear enhances rheotaxis. This implies that active particles are spending more time inside the channel contrary to passive ones under the same conditions since in their most probable orientation they are fighting the flow. These behaviors are not observed in passive particles, which at all times follow the streamlines as shown in Figure 3 trajectories 1–4.

The vectors in Figure 3 denote the orientation of the nanorods relative to the $x$-axis, in every 25 captured frames. In this setup, we are not able to distinguish the gold from the platinum side. Correspondingly, the measured angles are in the $\pm 90^\circ$ range. We observe that the alignment is a statistical result of the time the particles spend oriented with the flow. It is because during diffusion events, both passive and active nanorods constantly deflect from the aligned orientation. However, orientation and deviation, while illustrated similarly for both types of particles, is actually a result of two different types of motion as it will be demonstrated later by a mathematical model. For active particles, tilt angle and self-propulsion make the anti-parallel orientation stable and the parallel unstable, resulting in oscillations around the aligned orientation (See Movie 1, Supporting Information). Passive particles, with observed tilt angle, experience the effect of shear in the $y$-component, so they perform Jeffery orbits$^{[13]}$ (See Movie 2, Supporting Information).

For better visualization of the alignment, Figure 4 shows the probability of occurrence of a specific absolute value of the angle for passive and active particles in the channel and nozzle. We show absolute values because, without differentiating the head and tail of the particles, positive and negative angles are equivalent. Here we observe how the increase in flow rate enhances the alignment of both kinds of nanorods. In the channel, active particles are more rapidly aligned than passive ones, showed by their higher probability of orienting around 0°. On the other hand, inside the nozzle, alignment is very similar for both types of particles. We associate this effect on the rapid increase in flow velocity overwhelming the influence of self-propulsion and the weather-vane effect, hence, active and passive particles behave similarly. Although the trend in the distribution functions for passive and active rods in the nozzle
Figure 2. 2D histograms of nanorods horizontal orientation versus y-coordinate at different positions in the microchannel and three different mean flow speeds: 550, 165, and 55 μm/s. Position 1 being at the zone with parallel walls, and positions 2, 3, and 4 three different sections of the nozzle. Upper part passive rods and lower part active.
is similar, accumulating reliable statistics for active rods in the nozzle is challenging, especially for a high flow rate. In experiments, the concentration of passive rods can be much higher than that for the active ones; active rods at high concentrations generate gas bubbles by H$_2$O$_2$ decomposition and can clog the nozzle. As a result, for high flow rates, the dilute suspension of active rods passes the nozzle very fast, generating only a few reliable measurement events, and, correspondingly, poor statistics.

3. Computational Model

We develop an agent-based computational model to rationalize the physical behaviors of the nanorods in channels and nozzles. This model is a generalization of the one from ref. [29]. We assume that active nanorods swim at constant height $h_0 = 2\,\mu m$ above the substrate and the fixed polar orientation angle or, equivalently, the tilt angle $\phi = 13^\circ$. This assumption allows us to reduce consideration to a 2D model where each nanorod is described by its center location $r(t) = (x(t), y(t))$ and unit orientation vector $p(t) = (\cos \theta(t), \sin \theta(t))$. As nanorods in experiments swim far from each other during extrusion, we omit hydrodynamic and steric interactions between them. We also assume that nanorods do not alter the background fluid flow. Dynamics of $r(t)$ and $p(t)$ is determined by force and torque balances for a nanorod. As swimming occurs in a low Reynold’s number regime where inertia is negligible, dynamics of a nanorod is described by a system of two coupled stochastic differential equations at the overdamped limit, i.e., these equations are of the first order in time. Forces and torques exerted on a nanorod are due to extrusion by the background flow, nanorod self-propulsion, and steric interactions between the nanorod and walls. Note that the sum of electrostatic, hydrodynamic, and gravitational forces, resulting in the tilted configuration of nanorods, is already considered by the constraint that nanorods swim with the fixed tilt angle $\phi$.

To evaluate the drag force and torque exerted by the extruding fluid on the nanorod, we compute the background fluid flow $u(x, y, z)$ by solving the Stokes problem in channel and nozzle. Although the drag force is simply proportional to background fluid flow $u$, the formula for torque is more subtle due to the tilted swimming of the nanorod. Namely, the equation for $p$ reads as

$$\dot{p} = (1 - pp^T)[A p - \tan(\phi) \partial_z u + \text{rotational noise}]$$  \hspace{1cm} (1)$$

where $u = u_i + v_j$, $A = \nabla_x(u, v)$ (in other words, $A$ is the 2D projection of $\nabla u$), and $\partial_z u = (\partial_z u_i, \partial_z v_j)$. Without the second term in the right-hand side, Equation (1) is the modification of Jeffery’s equation$^{[33-35]}$ for a rod-shaped swimmer. We note that solutions of the classical Jeffery’s equation for ellipsoids are periodic and describes Jeffery’s orbits, whereas in our case, for nanorods (they can be thought of as ellipsoids with infinite aspect ratio), solutions are heteroclinic orbits connecting two steady states $p = i$ and $p = -i$ (i.e., swimming strictly downstream or upstream in channel with background flow $u = u_i$).

The second term in the right-hand side of (1) comes from the reorientation of the nanorod due to its tilted configuration. Specifically, the front of the nanorod is located closer to the substrate than its back, and the magnitude of the background fluid flow grows as one moves away from the substrate. Therefore, the nanorod experiences a torque from shear component in $z$, i.e., term $\partial_z u$. This term admits a simplification that allows excluding variable $z$ from consideration and making the model truly 2D. Indeed, $h_0 = 2\,\mu m$ is much smaller than the height of both

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Figure 3. Trajectories and orientation of nanorods flowing through the microchannel. 1–4 passive particles, 5–8 active particles. Mean flow speed 165 $\mu m\,s^{-1}$ (flow rate 3 $\mu l\,h^{-1}$). Scale bar = 10 $\mu m$. 

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channel and nozzle, $H_0 = 50 \mu m$. Then by the standard Taylor expansions one obtains

$$u(z,0) \approx h_0 \frac{\partial u}{\partial z} \bigg|_{z=h_0}$$

In view of no-slip boundary conditions $u|_{z=0} = 0$, one arrives to relation $u \approx h_0 \partial_z u$ for $z = h_0$, which allows replacing the derivative in $z$, $\partial_z u$, in (1) by $h_0^{-1} u$. This modification of (1) leads to the following interpretation of orientation dynamics which, roughly speaking, is that a nanorod exhibits two competing alignments. The first one is due to the $(x, y)$-gradient of $u$ (matrix $A$ in (1)): a nanorod tends to reorient such that $p = \frac{u}{|u|}$ (parallel to the flow) or $p = -\frac{u}{|u|}$ (anti-parallel to the flow), depending on whether front or back of the nanorod is located closer to the closest wall. The other alignment is due to term $h_0^{-1} \tan(\phi) u$, leading to anti-parallel reorientation, or, equivalently, swimming upstream. This alignment is precisely what we refer to in this work as the weather-vane effect, as a nanorod reorienting upstream is similar to the weather vane changing its direction to oppose the wind.

By performing numerical simulations, we obtained angular histograms for horizontal angle $\theta$ of both active and passive nanorods extruded through a channel and a nozzle, see Figure 4c,d. The histograms are in qualitative agreement with the ones obtained from experiments, Figure 4a,b. However, experimental histograms, depicted in Figure 4b, show that in nozzle, active nanorods are less focused at $\theta = 0^\circ$ than passive ones, whereas in simulation histograms, depicted in Figure 4d, relation between orientation of active and passive nanorods is similar to that in channel for both experiment and simulations: active nanorods are more aligned than passive ones. This difference is caused by the fact that streamlines of an incompressible flow in nozzle, whose lateral walls are converging, are not horizontal (as opposed to streamlines in the channel), but slightly directed toward the center-plane $z_c = 25 \mu m$. Therefore, passive nanorods, which follow the streamlines, are lifted in the nozzle.

Figure 4. Horizontal angle distribution in a,b) experiment and c,d) simulations for active (dashed lines) and passive (solid lines) particles in the channel and nozzle. An increase in the flowrate enhances alignment with the orientation of the channel. Distribution of active rods for mean flow speed $550 \mu m s^{-1}$ (b) is not accurate due to insufficient statistics.
In contrast, active nanorods, due to their tilted configuration, are self-propelled toward the bottom, thus resist lifting and maintain the same height. Since the larger height, the stronger the drag torque exerted on a nanorod, we obtain more focused orientation histograms for passive nanorods. We also note here another difference between aligning with streamlines in channel and nozzle: a perfectly aligned nanorod in the channel swims with orientation $\theta = 0^\circ$ (modulo $\pi$), whereas streamlines in nozzle are not parallel and correspond to a range of $\theta$, from $0^\circ$ to $\tan^{-1}(45/100) \approx 24.2^\circ$. This may result in a nonmonotonic distribution of $\theta$ in nozzle around $\theta = 0^\circ$; see, e.g., passive nanorods with $110 \mu m/s$ flow in Figure 4d. Finally, we simulated histograms $\theta$ versus $y$, depicted in Figure 5a–d, and observed that they are also similar to the results of experiment shown in Figure 2. In addition, active nanorod trajectories behave similarly in experiments and computations: they are straight at the center zone (around the centerline) and looping at the lateral zones (close to walls), see Figure 5e,f.

Next, we use our modeling approach to elucidate the difference in orientation dynamics of passive nanorods and active nanorods in various parts of the channel. We consider 2D Poiseuille flow in rectangular channel of width $2W$: $u = v_c(1 - (y/W)^2)$, $v = 0$, where $v_c$ is the flow velocity at the centerline of horizontal cross-section $z = h_0$. Then if $\theta(t)$ is the angle between rod’s orientation $p(t)$ and axis $x$ at time $t > 0$, then (1) implies the following ordinary differential equation for $\theta$

$$\dot{\theta} = -\frac{\partial u}{\partial y} \sin^2 \theta + \epsilon u(y) \sin \theta$$

(3)

where $\epsilon = h_0^{-1} |\tan(\phi)|$ for an active nanorod and $\epsilon = 0$ for a passive one. In settings of our experiments for active rods $\epsilon = 0.12 \mu m^{-1}$. Function $y(t)$ varies in time and solves another differential equation, but for the sake of simplicity we assume that $y$ is constant, so we study behavior of $\theta(t)$ solving (3), given $y$ as a parameter. In Equation (3), we also neglected noise (or, equivalently, rotational diffusion) to focus on how the background flow affects the nanorod’s orientation dynamics.

For a passively swimming nanorod, the weather-vane term vanishes, $\epsilon = 0$, so equation for $\theta$ becomes $\dot{\theta} = 2v_c y/W^2 \sin^2 \theta$. For $y > 0$, we have that $\dot{\theta} \geq 0$ and the
passive nanorod rotates counterclockwise only, with two semi-stable steady orientations $\theta = 0$ and $\theta = \pi$. If a passive nanorod initially points toward the closest wall (that is, $0 < \theta < \pi$), then the background shear turns the nanorod to face upstream, $\theta \to \pi$. Conversely, if the passive nanorod initially points away from the closest wall (that is, $-\pi < \theta < 0$), then the background shear turns the nanorod to face downstream, $\theta \to 0$. This behavior is illustrated by the angular diagram in Figure 6a. If rotational noise is considered in dynamics of $\theta$, then $\theta$ can “jump over” a semi-stable steady-state and converge to another steady-state. For an active nanorod, if the weather-vane term dominates in Equation (3) (for example, when the nanorod is located closer to the centerline, is where trajectories of active nanorods are straight and active rods reorient similar to passive ones (cf. Figure 6a,b). The emergence of a stable stationary orientation different from 0 or $\pi$, which we have for $|y| \geq y_{\text{crit}}$, leads to rapid changes in $y$ (recall that $\dot{y} = V_{\text{prop}} \sin \theta$) and, as a consequence, changes in orientation as its dynamics depends on $y$. This explains why in the lateral zone, as opposed to the central one, active nanorods

![Figure 6](image_url)

Figure 6. Orientation dynamics of passive and active nanorods in various distances from the centerline in the channel. Passive rods are colored black (a,b), whereas active rods have yellow back half and black front half, illustrating its gold–platinum structure, (c–g) and (c’–g’). The background flow is sketched by arrows on the left-hand side of the figure. For each rod, dynamics is described by a circle around it, where a point on the circle corresponds to angular orientation $\theta$, as depicted in the inset. White, black, half-black/half-white small circles denote unstable, stable, and semi-stable stationary orientations $\theta$, respectively. Arrows on angular circles indicate turning directions (clockwise or counterclockwise). For example, nanorod in (a) is passive and turns counterclockwise with two semi-stable orientations $\theta = 0$ and $\theta = \pi$; nanorod in (c) is active and it turns counterclockwise if $0 < \theta < \pi$ and clockwise if $0 > \theta > -\pi$, whereas $\theta = 0$ and $\theta = \pi$ are unstable and stable stationary orientations, respectively. Orientations of nanorods inside their angular circles as well as their $x$-locations are chosen randomly.
do not swim straight but instead exhibit looping trajectories. We note that in our experimental settings with \( r = 0.11 \, \mu \text{m}^{-1} \) and \( W = 50 \, \mu \text{m} \) we have that \( \gamma_{\text{crit}} = 45.66 \, \mu \text{m} \) which is close to the wall, whereas the active nanorods exhibit looping trajectories for larger distances from the wall. This is because even for sub-critical (but close to critical) values of \( \gamma \), though there is no steady direction toward the centerline, the angular dynamics, given by the right-hand side of Equation (3), is slow, and in this case rotational diffusion dominates, leading to nonstraight trajectories. However, for sub-critical values \( \gamma \), close to the centerline, impact of background flow dominates the rotational diffusion and trajectories are straight, as it follows from analysis of Equation (3).

4. Conclusion

We show that passive and actively swimming nanorods both qualitatively and quantitatively behave differently in microfluidic channels and nozzles. In a microchannel with parallel lateral walls, the passive nanorods tumble in the shear flow. The differential torque across the length of the nanorod leads to a random distribution of orientations and alignments. In contrast, the active nanorods are stable across a range of shear flows because their self-propulsion force counterbalances the fluid torque. The balance of forces leads to realignment anti-parallel to the flow and persistent, linear trajectories.

We experimentally test the passive and active nanorods in microscopic nozzles. Our micronozzles are similar to filament extrusion nozzles in direct-ink-writing (DIW) 3D printers. We demonstrate the differences between passive and active nanorods. The passive nanorods are randomly distributed in low shear flows. As the shear increases, the passive nanorods increasingly align either parallel or anti-parallel to the flow. The nanorods are most strongly aligned near the nozzle outlet where shear is highest. In contrast, active nanorods show an innate adaptive behavior to changing shear. The active nanorods realign anti-parallel to the converging fluid streamlines. As shear increases, the particles orient along the streamlines and rapidly converge with an ordered alignment. The active nanorods are extruded through the nozzle outlet with precise orientations and alignment.

We further elucidate how to control the orientations and alignments in active nanorods. Our computational model rationalizes how the stable trajectories of active nanorods arise due to their activity. The balance of forces due to self-propulsion and viscous drag leads to the active nanorods realigning in an adapting anti-parallel alignment to the flow. The active particles then behave like a weather vane and oppose the fluid flow. The weather-vane effect instills specific alignment and orientation of the active particles through both parallel and converging streamlines. Thus, by developing different nozzle geometric features, such as bumps or teeth, one can create nontrivial streamlines and then prescribe more complicated orientations and alignments.

We speculate that the future of 3D DIW printing will utilize quick-changing filaments and printing additives to create complex materials with precise voxel by voxel properties for soft robots. Future extrusion nozzles can be designed to orient and align self-propelled particles in specific patterns and distributions. The more precise control of orientations and alignments would enable users to 3D print composite structures with either anisotropic or isotropic material composition. Furthermore, the active particles themselves are not limited to bimetallic nanorods, they could include lining cells or bacteria. With recent developments in nanoscale 3D printing, one can print highly reproducible anisotropic self-propelled particles with chiral geometry. The chiral geometry would enable more complex responses to shear flows and alignment to streamlines. This would provide users with more control over their 3D printing additives and material composition in the final structure. However, to develop smart additives using active particles, significant advances in efficient self-propulsion through viscous environments, such as liquid polymers in 3D printers are needed.

5. Experimental Section

Gold–Platinum (Au–Pt) nanorods were fabricated by electrodeposition in anodic alumina membranes and then freed following the procedures described in ref. [42]. Microfluidic channels were fabricated using the Dow Sylgard 184 PDMS Kit (1:8 curing ratio) using a soft lithography SU-8 mold on a silica wafer. The PDMS component was mounted onto a microscope coverslip using a hand-held plasma gun. The channels had a constant height of \( h_0 = 50 \, \mu \text{m} \) and an overall length of 1.5 cm and it was divided into three sections: parallel walls for the inlet, the converging walls for the nozzle, and parallel walls for the outlet. Width between walls for the inlet and outlet was \( \approx 100 \, \mu \text{m} \). The length of the nozzle section was 100 \( \mu \text{m} \).

The microfluidic device was connected to a 250 \( \mu \text{L} \) Hamilton glass syringe mounted on a CETONI neMESYS low pressure syringe pump using polyethylene tubing. Precipitation of 2 \( \mu \text{m} \) long gold–platinum (Au–Pt) bimetallic nanorods was first shaken in an ultrasound cleaner to suspend the particles in the water (H2O). For active particles, 30\% H2O2 was added until a final concentration of 15\% was achieved for ensuring nanorods maximum self propulsion speed. Although particles were suspended in the vial, the system was filled via the outlet ensuring no air bubbles were introduced. We then analyzed the behaviors of passive and actively swimming nanorods at 1, 3, and 10 \( \mu \text{L} \, \text{h}^{-1} \). The experiments were run on an Olympus IX-83 inverted microscope with a 40\times objective. We recorded the videos at 100 frames per second on a Hamamatsu ORCA-Flash4.0 V3 CMOS camera.

Image Analysis: Image and data analysis was performed with a custom MATLAB script. From each frame, particles were identified and geometrical properties such as size, orientation, centroid, and area were extracted. A tracking function allowed for the reconstruction of the trajectories. CFD simulations in COMSOL were used to obtain the data of the fluid flow velocity profile and shear stress in the channel and nozzle.

Supporting Information

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

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Conflict of Interest
The authors declare no conflict of interest.

Author Contributions
L.D.R., M.P., and R.D.B. contributed equally to this work. I.S.A., L.B., and A.S. conceived the research. L.D.R. designed and fabricated the lithographic molds, soft PDMS channels, and bimetallic nanorods. L.D.R. and R.D.B. performed the experiments together. L.D.R. developed and ran the image processing algorithms. M.P. developed and performed the confined self-propelled nanorod simulations. All authors discussed the results and wrote the article.

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active matters, bio-inspired, microfluidics, microscopic nozzles, self-propelled colloids, smart additives

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