Active colloidal microdrills†

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We demonstrate a chemically driven, autonomous catalytic microdrill. An asymmetric distribution of catalyst causes the helical swimmer to twist while it undergoes directed propulsion. A driving torque and hydrodynamic coupling between translation and rotation at low Reynolds number leads to drill-like swimming behaviour.

Propulsion at the micro and nanoscale1 can be achieved by a wide range of methods including the use of light,2 bi-molecular motors,3 acoustics,4 thermophoresis,5 and enzymes,6 as well as electric,7 and magnetic fields.8 One of the most popular routes is chemical propulsion due to the lack of a need to introduce an external driving force. A typical system of this type is a nano9 or microstructure which consists of an on-board catalyst.10 This type of motor catalyzes a locally available chemical fuel and thereby gives rise to self-phoretic locomotion. In recent years, many systems of this type have been studied, and a wide range of architectures and morphologies have been demonstrated. The most common are the following: asymmetric half-coated micro Janus spheres,11,12 bi-metallic nanorods,13 microjet microtubes,14 and shell motors,15 just to name a few. The listed examples are usually structurally symmetric (e.g. spherical), and the asymmetry necessary for proper motion is primarily due to an asymmetric distribution of catalyst on the structure. However, structurally asymmetric autonomous micromotors display swimming behaviour that is not observed in their symmetrical counterparts and therefore warrant investigation.

For micromotors of complex shape, an intricate interplay between the driving force and hydrodynamic interactions exists, yet this can be advantageous. Since the shape and material composition of active colloidal particles dictate the type of swimming behaviour observed, desired motion characteristics can be engineered into the system if the micromotor fabrication process can be precisely controlled. Here we show that by using a dynamic fabrication technique, we can manufacture several billion microdrills that are catalytically active and at the same time structurally anisotropic. These chemically propelled colloidal swimmers undergo coupled translational and rotational motion in a corkscrew type movement. Although the motors exhibit a range of different swimming behavior, the one we focus upon is autonomous corkscrew motion, as this is the basis of any screw or drill.

This motion is a result of simultaneous material and geometric asymmetries made possible by the fabrication process. In particular, the swimmer consists of a spherical head with a helical tail, in the shape of a corkscrew, in which both the head and the helix backbone consist of silica, SiO2. The spherical heads in this case are 1 μm microbeads, and the helix tail is fabricated using glancing angle deposition (GLAD) which is a dynamic physical vapor deposition process.17 GLAD uses vapour incidence angles α ~ 85°. The microbeads act as seeds for the accumulation of material during GLAD growth and ensure a higher structural uniformity. By combining grazing incidence with simultaneous substrate rotation, the tail can be grown in a helical fashion.

The total length of the catalytic microdrills (including the spherical head), major diameter, minor diameter, pitch (threads per length), and thread angle are l = 4 ± 1 μm, D = 1400 ± 200 nm, d = 630 ± 70 nm, p = 1330 ± 80 nm, and θ = 32 ± 5°, respectively (see ESI†). In this case, the threads of the microdrills are left-handed, dictated by the rotation sense of the substrate during the deposition. It should be noted that the variation in the total length, l, is due to the competitive growth which is typically seen in GLAD.17

Platinum (Pt), which acts as the onboard catalyst, is coated onto the structures in an asymmetric manner. This asymmetric
distribution of the catalyst is critical for propulsion, as is well known. The schematic in Fig. 1(a) shows how platinum (Pt) is deposited at a normal incidence angle, $\alpha = 0^\circ$, onto a 1-turn helix, so that Pt will only coat one side. By repeatedly growing individual single turns followed by the procedure shown in Fig. 1(a), the resulting structures, shown in the cross-section scanning electron micrograph (SEM) image in Fig. 1(b), can be fabricated. By using an energy selective backscattered (ESB) electron detector, the contrast between the SiO$_2$ (darker contrast) and the Pt (lighter contrast) can be easily distinguished in the image. The details of the fabrication process, morphological characterization, and other experimental procedures and conditions, such as particle tracking etc., can be found in the ESL.$^\dagger$

The particles are easily separated, removed from the substrate, and suspended into a colloidal suspension by ultrasonication for $\sim 10$ s. Individual separated and removed microdrills can be seen in the optical microscope image of Fig. 1(c) in which the particles have settled on the surface of the microscope slide. Here, they undergo effectively 2D diffusion, due to partial confinement to the surface by gravity, brought on by thermal movement of the surrounding solvent molecules. Two example videos of single particles undergoing Brownian motion in H$_2$O alone can be found in the ESL.$^\dagger$ The diffusion coefficient (for a sphere) of radius $R$ is given by $D = k_B T / 6 \pi \eta R$, where $k_B T$ is the thermal energy, and $\eta$ is the fluid viscosity. The diffusion constant was determined by calculating the mean squared displacement (MSD) for five diffusing particles and was calculated to be $D = 0.35 \pm 0.01 \, \mu$m$^2$ s$^{-1}$.

When hydrogen peroxide, H$_2$O$_2$, is added, the motors’ behavior is dramatically changed. The thin coating of Pt is sufficient to catalyze the decomposition of H$_2$O$_2$ into reaction products: O$_2$ and H$_2$O. A comparison of a single particle diffusing in H$_2$O vs. an active particle in H$_2$O with added H$_2$O$_2$ is shown in Fig. 2. A marked difference in the translational movement can be seen for the same length of time, i.e. 5 s. The changes in direction are caused primarily by rotational Brownian motion.

It has been shown that typically for a system in which the autonomous swimmer consists of a catalyst on an electrically insulating material, the motor will be propelled away from this site where the reaction is occurring. The direction of propulsion for catalyst-on-insulator motors has been established$^{12,16}$ and suggests that the microdrills are propelled away from the catalyst site. In the ensemble of microdrills, we, however, also find a wide variety of motion behavior, such as pure translation, spinning about the helix axis while translating (microdrill motion), spinning perpendicular to the helix axis with little translation, and end-over-end rotation (tail movement side-to-side). Table S1 in the ESL.$^\dagger$ summarizes the statistics for 134 swimmers chosen at random. These variations are attributed to inhomogeneity amongst both particle morphology and catalyst coating. Videos of each type of movement can also be seen in the ESL.$^\dagger$ with several showing microdrill movement ($\sim 25\%$ undergo this type of movement).

We focus our attention on this type since, to the best of our knowledge, autonomous movement of this kind has never been characterized to date, although a roughly similar structure was briefly characterized once before.$^{18}$ Microdrills that are undergoing both rotational and translational movement near the solid–liquid interface display the following traits: as seen in Fig. 3, the translational speed is a function of time. The rotation rate is also directly related to translational speed as well; as the rotation rate increases, so does the translational speed. The typical behavior observed is the following: translation with slow rotation occurs for a short interval, followed by quick rotation at which time the translational speed increases. For the swimmer in Fig. 3, this cycle repeats with a periodicity of $\sim 6\pi$ rad s$^{-1}$. The numbers above the peaks in the example of Fig. 3 show the completion of one full rotation at which time the particle’s rotation rate and translational speed again slow, then the cycle

![Fig. 1](image1.png)

![Fig. 2](image2.png)

![Fig. 3](image3.png)
The variation in orientation of the microdrill for each half turn repeats. The exact nature of the speed changes is not fully understood, but observation suggests they arise due to interactions with the surface, as the microdrill exposes the catalyst towards the substrate and then away from it as it rotates.

Fig. 4 details how the rotational motion is verified. The left column shows sequential frames from a video which correspond to π rad rotations. The position of the frame in this case is fixed to show translation. The center and right columns focus upon axial rotation. The Pt coating can be clearly resolved (darker color) with bright-field microscopy, allowing for the observation of the rotational orientation. The light colored lines are added in the right column to highlight the relative angle between the drill threads and the helix axis – clearly showing rotation.

Notes and references


