Microscopic metavehicles powered and steered by embedded optical metasurfaces

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Nanostructured dielectric metasurfaces offer unprecedented opportunities to manipulate light by imprinting an arbitrary phase gradient on an impinging wavefront1. This has resulted in the realization of a range of flat analogues to classical optical components, such as lenses, waveplates and axicons2–4. However, the change in linear and angular optical momentum5,6 associated with phase manipulation also results in previously unexploited forces and torques that act on the metasurface itself. Here we show that these optomechanical effects can be utilized to construct optical metavehicles—microscopic particles that can travel long distances under low-intensity plane-wave illumination while being steered by the polarization of the incident light. We demonstrate movement in complex patterns, self-correcting motion and an application as transport vehicles for microscopic cargoes, which include unicellular organisms. The abundance of possible optical metasurfaces attests to the prospect of developing a wide variety of metavehicles with specialized functional behaviours.

One of the most distinguishing features of optical metasurfaces is their ability to simultaneously manipulate a wave’s propagation direction and polarization despite being subwavelength in thickness. This results in an exchange of linear and angular momentum between light and matter and, by virtue of Newton’s third law, optical forces and torques that act back on the metasurface (Fig. 1a). Artificial micro- and nanostructures designed to convert optical linear and angular momentum into mechanical motion were previously realized in several formats. Stationary optically driven nanomotors were shown to rotate in focused light fields due to a birefringent polarization conversion8, and through transfer of spin or orbital angular momentum of light via absorption and scattering9–11. Plasmonic dimer structures trapped in line foci by optical gradient forces were shown to be capable of directional movement due to asymmetric scattering patterns12,13. Structured microscopic objects were also shown to be able to translate in unfocused light fields due to refraction through curved surfaces14, reflection from angled micromirrors15, or diffraction from liquid-crystal gratings16, although these studies did not provide the means to control the propagation direction of the microparticles. Our proposed idea of using polarization-sensitive metasurfaces as dynamic elements removes the need for confining gradient forces in optical manipulation and enables free but controllable two-dimensional movement in plane waves. The basic idea is related to the recently proposed theoretical concept of self-stabilizing photonic levitation of nanostructured macroscopic objects17 in the sense that both rely on an ability to self-correct the orientation, and hence the motion, using optical torques.

Two main challenges need to be overcome to exploit this phenomenon for the practical realization of microparticles capable of movement and steering in a plane-wave light field. First, the microparticle should contain a metasurface that efficiently deflects light towards a specific deflection angle θ, such that a directed reaction force $F_{\text{opt}}$ is induced through the conservation of linear optical momentum. Second, the metasurface should be able to alter the angular momentum of light in such a way that a directed reaction torque $\tau$ appears; this will allow the microparticle to be steered through the control of the incident polarization while being driven forward. We fulfilled these criteria by incorporating a high-index dielectric metasurface (Fig. 1b), constructed as a lattice of anisotropic meta-atoms18, into a low-index transparent host particle to form a metavehicle (Fig. 1c). Directed propulsion was achieved by allowing only one of the principal lattice axes to support propagating diffraction orders and by designing each meta-atom as an asymmetric dimer nanoantenna, which enabled directive diffraction into only one of these orders. Furthermore, the dimer nanoantennas were elongated along the propulsion direction, which resulted in an anisotropic polarization response (shape birefringence) that caused alignment of the metavehicle along the incident (linear) polarization vector19–20 (see Methods for a detailed theoretical treatment).

The metavehicles were designed for operation in water using 1,064 nm plane-wave illumination. The high-index metasurface consisted of polycrystalline Si and the low-index host material was SiO2. Fabrication was based on a combination of material deposition, electron-beam lithography (EBL) and anisotropic etching, followed by suspension in water (Methods and Supplementary Fig. 1). The lattice constants were set, due to fabrication constraints, to $\Lambda_x = 600$ and $\Lambda_y = 950$ nm (in the propulsion direction), which corresponds to a deflection angle $\theta \approx 57^\circ$. Combined numerical and experimental optimization of metasurface parameters (Methods and Supplementary Fig. 2) to simultaneously ensure a maximal lateral momentum transfer and a substantial in-plane torque resulted in the dimer antenna lengths $L_x = 270$ and $L_y = 400$ nm, width $W = 200$ nm, height $h = 460$ nm and gap distance $g = 50$ nm (Fig. 1a inset). An optimized structure is displayed in Fig. 1b. Below we focus on the results for metavehicles with overall dimensions $12 \times 10 \times 1 \, \mu \text{m}^3$, although other sizes were also investigated.

Figure 2 displays optical properties crucial to propulsion and steering for the case of an optimized metavehicle. For a normal-incidence near-infrared plane wave polarized parallel to the nanoantenna’s long axis, simulations indicated that the metavehicle...
will be propelled by a reactive optical force component that deflects light at an angle $\theta$.

**Fig. 2 | Optical properties enabling metavehicle propulsion and steering.**

**a.** Beam-deflecting properties of the metasurface that caused the metavehicle propulsion force, $F_{\text{opt}}$. Left: simulated spectra for near-infrared transmission into 0 and ±1 diffraction orders for normally incident light polarized along the long axis of the nanoantenna (as indicated by the inset metasurface unit cell). Right: corresponding experimentally recorded diffraction efficiency at $\lambda = 1,064$ nm, also marked with dots of corresponding colour in the left figure. **b.** Calculated steering torques ($\tau_x$) normalized to the torque generated by the complete absorption of a circularly polarized beam ($\tau_z$). Left: transferred torque for normally incident 1,064 nm light with linear polarization aligned at angle $\psi$ with respect to the propulsion direction. The data imply that the metavehicle experiences a restoring torque that aligns its long axis with the polarization direction. The maximal restoring torque occurs for $\psi = 45^\circ$. Right: the metavehicle experiences a constant torque that is independent of metasurface orientation for circularly polarized light.

To verify that the optimized geometry also provides the expected restorative torque in response to polarization, we calculated the $z$ component of the integrated total spin density and extracted the reaction torque (Methods). For linearly polarized light, the spin angular momentum (SAM) transfer depends on the alignment angle $\varphi$ between the nanoantenna’s long axis and the polarization direction, and results in a restoring torque that strives to align the long axis with the polarization direction.

**Fig. 1 | From stationary metasurfaces to mobile metavehicles.**

**a.** Optical metasurfaces can manipulate the direction and polarization of transmitted light, but they are typically viewed as stationary objects that do not themselves react to the light’s altered momentum. However, by incorporating an engineered metasurface into a microparticle, the changes in linear and angular momentum can be employed to propel and steer the microparticle across a surface. We call such an object a metavehicle. In a plane wave with momentum $k_x$, incident along $Z$ and linearly polarized along $X$ (indicated by $E_{\text{pol}}$), a metavehicle that deflects light at an angle $\theta$ will be propelled by a reactive optical force component $F_{\text{opt}}$ in the plane of the supporting surface. If the metavehicle’s $x$ axis is oriented at an angle $\varphi$ to the polarization direction $X$, it will experience an alignment torque $\tau_x$ towards the polarization direction. Inset: the metasurface unit cell with relevant dimensions. **b.** Scanning electron microscopy images of a fabricated optimized metasurface that functions as an anisotropic directional beam deflector. **c.** Scanning electron microscopy image of a metavehicle that contains the same kind of metasurface.
metavehicle with the input polarization (Fig. 2b left). This implies that the metavehicle will self-correct its orientation to maximize the reactive force due to linear momentum transfer. The effect is maximized at \( \phi = \pm 45^\circ \), as for an electric dipole in an applied static field. For circularly polarized incidence (Fig. 2b right), the metavehicle experiences a torque in the same direction as the handedness of the incoming light. For symmetry reasons, this torque is independent of the alignment. However, as the circularly polarized wave will also be partly deflected, the combined angular and linear momentum transfer results in an orbital motion (that is, the net effect is a spin-to-orbital angular momentum transfer).

Translation and rotation dynamics were examined with metavehicles sedimented on the bottom glass of a thin sample cell filled with water. A 1,064 nm laser beam loosely focused to a diameter of \(~0.4 \text{ mm}\) and incident from above emulated a plane wave (Methods and Supplementary Fig. 5). The metavehicles travelled freely along the glass/water interface without the need to move the microscope stage nor the illumination position. Optical gradient forces and thermal effects were negligible for the power levels used (light intensity \( I < 20 \mu \text{W} \mu \text{m}^{-2} \) or power per metavehicle \( P < 2 \text{ mW} \)).

As anticipated from the design considerations and the equations of motion (Methods), the metavehicles propagated along straight lines directed by the incident laser light polarization and moved a distance proportional to the time-integrated applied intensity (Fig. 3a,b and Supplementary Video 1). For circular polarization, the metavehicles instead continuously turned while being propelled, with the orbital direction determined by the handedness of the incident light (Fig. 3c,d and Supplementary Videos 2 and 3). Tracking of the metavehicle movement with increasing laser power showed that the average speed increased linearly with light intensity (bottom panels of Fig. 3e,f), but with an about 50% lower proportionality constant for orbital motion because the propulsion \( x \) axis...
Fig. 4 | Metavehicles in complex and parallel motion and as transport vehicles. a,b. The metavehicles can be guided to follow user-controlled trajectories by controlling the polarization state of the incident light during travel. The line colour of each trace indicates the instantaneous speed, and the lower parts indicate the applied polarization state. The averaged laser intensity in the beam was 7.5 µW µm⁻² in a and 16 µW µm⁻² in b. c, Example of several metavehicles being driven in parallel at an intensity of 16 µW µm⁻² and linear polarization oriented in the vertical direction of the image. d,e. The metavehicles can function as transport vehicles for cargo delivery on an interface. The objects being transported, marked by green rings, are a ~4.2 µm diameter polystyrene microbead in d and a yeast cell in e. The cargo trajectories are shown in green, and position fluctuations of adjacent objects, due to Brownian motion, are indicated by blue traces. The applied intensity was 16 µW µm⁻² in both d and e.

The speed acquired by a metavehicle in water at low Reynolds numbers is set by the balance between the optical propulsion force and the viscous drag force to yield \( v = F_\text{opt} / \gamma_\text{D} \), with \( F_\text{opt} \) being the reaction force from equation (2) and \( \gamma_\text{D} \) the translational drag coefficient. We estimated the average drag coefficient as \( \gamma_\text{D} \approx 4.7 \times 10^{-7} \text{ kg s}^{-1} \) by a simple experiment in which the whole sample cell was tilted and the metavehicles steady-state sliding speed along the surface was measured (Supplementary Fig. 8a). Finite-element simulations of the flow around a moving metavehicle indicated that the experimental \( \gamma_\text{D} \) value corresponds to a physically reasonable surface separation distance of around 320 nm (Methods and Supplementary Fig. 8b). Using this, together with the calculated values of optical linear momentum transfer versus intensity, yields the dashed lines in Fig. 3c,f, which agree well with the measured metavehicle speeds for both linear and circular polarization. Data for metavehicles with about four times larger area also agree well with the theoretical model (Supplementary Fig. 9). Further, from the theoretical models for translation and turning speeds, a prediction of the metavehicles’ average turning radius \( R_\text{T} = \frac{v}{\gamma_\text{D}} \) is estimated to be ~30 µm, in good agreement with the observations (see the dashed line in Fig. 3f (top) and Methods for details).

The metavehicles can be made to drive in complex patterns by changing the polarization state of the incident light during propagation. Figure 4a,b and Supplementary Videos 4 and 5 give examples of two trajectories traced out by manually shifting between linear and circular polarizations at discrete points in time during the movement. Automatized computer-driven feedback and a more sophis-
ticated intensity and polarization control would allow even more advanced navigation. Moreover, as the illuminated area is much larger than that of a single metavehicle, it is possible to drive several vehicles in parallel (Fig. 4c and Supplementary Video 6). Further increasing the concentration of metavehicles in the suspension would enable large numbers of particles to simultaneously travel over a surface, all driven by the same incident light field, which provides an interesting platform to study interparticle interactions and collective phenomena in active matter.

We finally examined the metavehicles’ ability to transport other types of microscopic objects introduced into the suspension. Figure 4d and Supplementary Video 7 demonstrate controlled lateral pushing of a ~4.2 μm diameter polystyrene bead over a distance of ~0.2 mm. The surrounding beads served as tracer particles to attest that no other substantial forces or flows were present in the environment. This type of transport event usually ends with the bead sliding off the front of the metavehicle, a problem that is likely to be avoided by designing the front face with a U-shaped profile to match that of the intended cargo. Figure 4e and Supplementary Video 8 give a second example of transport that involves a single baker’s yeast cell (Saccharomyces cerevisiae). The low relative density of the cells means they tend to slip over the thin metasurfaces when mixed in pure water. However, this was countered by performing experiments in a weak salt solution (40 mM NaCl) to slightly decrease the electrostatic repulsion between the cells and the substrate surface. We note that the use of near-infrared illumination and metasurfaces that exhibit negligible optical absorption greatly reduced the risk of biologically harmful photodamage or heating of the cells. Both the polystyrene beads and the yeast cells slightly increased the overall drag coefficient of the metavehicle–cargo system, but the effect was too small to cause a noticeable slowdown of movement. The metavehicles also transported much larger objects, as illustrated in Supplementary Video 9 in which a dust particle about 15 times the size of a metavehicle is pushed over a considerable distance, albeit with a somewhat impaired steering efficiency.

In summary, we show that it is possible to construct metavehicles that are able to propagate freely across a surface in plane-wave illumination and that can be steered by control of the incident polarization. The multitude of possible optical metasurfaces offers a wealth of opportunities to introduce novel functionalities to light-driven objects. For example, Pancharatnam–Berry phase-gradient metasurfaces23 could be used to control propagation through the handedness of polarization, metasurfaces constructed as high-numerical-aperture flat lenses could function as miniature laser tweezers and spatially multiplexed22 or colour-routing31 metasurfaces could be used to build metavehicles capable of altering their functionalities depending on the illumination wavelength. Metavehicles could also include molecular-sensing functionalities24 or allow for additional complementary propulsion mechanisms.

Online content
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Methods

Theoretical basis for beam deflection and spin transfer. Consider a two-dimensional periodic structure with lattice constants $\Lambda_x$ and $\Lambda_y$, embedded in a homogeneous isotropic host medium with refractive index $n$. According to Bloch's theorem, a normally incident plane wave is scattered into a wave number of diffraction orders that can be labelled by the in-plane wavevector $\mathbf{k}_j = \left( \frac{2\pi j}{\Lambda_x}, \frac{2\pi k}{\Lambda_y} \right)$. For incident light with a free space wavelength $\lambda$, only orders with $|\mathbf{k}_j| < \frac{\lambda}{2}$ are propagated. To enable propulsion along the x direction but not along the y direction, the metasurfaces are designed to have $\Lambda_y < \frac{\lambda}{2}$. This allows diffraction orders to propagate in the $m=0$ subspace but suppresses all $m \neq 0$ orders.

Rigorous calculation of the optical force and torque requires surface integration of the stress tensor around the object. Here we follow a simpler approach based on the summation of diffraction order moments, which nevertheless yields the correct result. Let $e_{xj}$ be the complex electric far-field amplitude in propagating diffraction order $(m,n)$. The in-plane linear momentum density carried by each diffraction order within the $m=0$ subspace is $p^{(m)} = \frac{1}{2} |e_{xj}|^2 \sin \theta_{0,j}$, where $\eta = \sqrt{\mu_e/(\epsilon_0 c^2)}$ is the impedance of the host medium, $c$ is the speed of light in vacuum and $\theta_{0,j}$ is the angle between the normal and the propagation direction (SI units are used). Taking into account the surface area $A$ of the object and collimation (narrowing) of the diffracted beam cross-section by a factor $\cos \theta_{0,j}$, the total in-plane linear momentum flux carried away by each order $P_x^{(m)} = \frac{1}{2} |e_{xj}|^2 \sin \theta_{0,j} \cos \theta_{0,j}$, or, equivalently, by the Poynting vector (intensity) $S_x = \frac{1}{2} \epsilon_0 c |e_{xj}|^2$ of each diffraction order, $P_x^{(m)} = \frac{1}{2} \Lambda_x A \sin \theta_{0,j} \cos \theta_{0,j}$.

Therefore, by designing the metasurface such that $e_{xj} \neq e_{x,j+1}$, we can enable the in-plane momentum transfer from the electromagnetic field to the object.

To enable steering of the metavehicle by incident polarization, the metasurface was designed to be anisotropic, that is, with different responses for the x- and y-polarized incident light. This anisotropy allows us to convert the spin of the incident light, and thus induce torque (spin transfer) on the structure. Our aim is that the structure should align with the incident polarization state of light that causes the in-plane propulsion. To simultaneously fulfill the two requirements of propulsion and steering, we have considered a two-dimensional optical metasurface cell with respect to the $x$ and $y$ vertical axis per unit area is the SAM flux

$$S_x = \frac{1}{\Lambda_x A} \sum_j \left( T_{x,j} + R_{x,j} \right) \sin \theta_{0,j}$$

(Nature Nanotechnology 10, 917–922 (2015)).

To assess the intensities $S_x$ of each diffraction order, we numerically simulated the transmitted and reflected coefficients $T_{x,j}$ and $R_{x,j}$ of propagating diffraction order. Recalling that transmission coefficients $T_{x,j}$ describe the projection of the time-averaged Poynting vector of scattered orders ($S_x$) on the $z$ axis, $T_{x,j} = (S_x \cos \theta_{0,j})$, we obtained an expression for the total in-plane momentum transfer per unit area of the object.

$$F_{opt} = F_x = -\Delta P_x$$

whose maximal value is realized by a complete diffraction of the incident radiation into a $-1$st (or $-1$st) diffraction order, $F_{opt} = \Delta P_x A \sin \theta_{0,j}$.

The spin transfer from a normally incident wave was assessed by calculating the time-averaged SAM densities $s_x$, of the total transmitted and reflected fields, $E$ and $H$ are the electric and magnetic fields of the total transmitted and reflected field, respectively:

$$s_x = \frac{1}{4\omega} \text{Im} \left[ e_{xj}^*E \times E + \mu_x H \times H \right]$$

Spin continuity allows us to calculate the total scattered SAM per unit area by integrating the SAM density over the unit cell $\Lambda_x A$, in a horizontal plane away from the structure, and adding up the transmitted and reflected contributions:

$$\left( \frac{s_{x \text{net}}}{A} \right) = \frac{1}{\Lambda_x A} \int s_x \, dx \, dy$$

When the structure is excited by linearly polarized light, the incident SAM is zero, and the spin transferred to the structure is minus the total scattered spin, whereas for circularly polarized light it is simply the difference between the incoming and outgoing SAM. Thus, the torque $\tau$, exerted on the structure along the vertical axis per unit area is the SAM flux:

$$\tau = \frac{-c \eta \mu_x (s_{x \text{net}}) - (s_{x \text{net}})}{A}$$

Correspondingly, the reaction torque for linearly polarized incidence maximizes when the outgoing light is circularly polarized, $\tau_{max} = \frac{-c \eta \mu_x (s_{x \text{net}})}{A}$. In the case of circularly polarized incidence, the maximum spin transfer happens when the metasurface reverses the handedness of the re-emitted light and the metavehicle experiences a reaction torque of $\tau_{max} = \frac{c \eta \mu_x (s_{x \text{net}})}{A}$.

Equations of motion. For a particle with a rigid anisotropic shape, such as those considered in this work, the equations of motion in the body frame of the moving particle can be written in compact form as:

$$\dot{\mathbf{v}} = \mathbf{F} - \mathbf{B}$$

where $\mathbf{F}$ is the hydrodynamic friction tensor, $\mathbf{V} = (\omega, \chi)$ is a generalized vectorial velocity with $\mathbf{v}$ the particle's translational velocity and $\omega$ its angular velocity, $K = (F, T)$ is a generalized effective vectorial force with $F$ being the force and $T$ the torque acting on the particle and $\mathbf{g}$ is a random vector with correlation $2\kappa_4 T \mathbf{f}^2 (t)$. Note that equation (6) is in the overdamped limit, in which the inertial term is dropped to account for the fact that the motion occurs in the low-Reynolds-number regime. Furthermore, although equation (6) is given in the body frame ($xyz$ in Fig. 1) of the moving particle, where $\eta$, $V$ and $K$ are constant, it can straightforwardly be transformed to the laboratory frame ($XYZ$ in Fig. 1).

For the system and particles we are considering, several simplifications can be introduced to equation (6). Specifically, (1) the hydrodynamic friction tensor $\eta$ is diagonal (in the body frame of the moving particle, that is, $xzy$) because of the reflection symmetries of the particle around its main axes and (2) the particles can be considered to be moving in two dimensions because the metavehicles reside at a glass interface and the gravitational force is balanced by the buoyancy force and double-layer repulsion from the glass interface. Moreover, as the metasurface absorption is low, the potential absorptive radiation pressure that acts in the laser's incident propagation direction (along Z) is, at these laser intensities, small and does not noticeably alter the force balance in our system. Together these simplifications allow us to greatly simplify and rewrite equation (6) in the body frame of the moving particle by only considering the translational (T) motion of the particle in the $xy$ plane and its rotational (R) motion around the $z$ axis. The resulting set of Langevin equations is:

$$\dot{\mathbf{v}} = \frac{D_T}{m} (F_x + \sqrt{2D_T/\tau_{max}x})$$

$$\dot{\omega} = \frac{D_R}{m} (F_y + \sqrt{2D_R/\tau_{max}y})$$

where $D_T$ and $D_R$ are the diffusion coefficients along the major axis of the particle ($x$ direction), the minor axis of the particle ($y$ direction) and its in-plane rotation (around the $z$ axis), and $v_{x, y, z}$, and $\omega_{x, y, z}$ are independent white-noise stochastic processes with zero mean and unitary variance.

The translational and rotational diffusion coefficients are linked to the corresponding drag coefficients $D_{x, y, z}$ and $D_{x, y, z}$ according to the fluctuation–dissipation relations $D_{x, y, z} = \frac{k_B T}{\gamma_{x, y, z}}$. The metasurface has an $xy$ aspect ratio of $\approx 1:2:1$, and hence the translational drag coefficients along the main principal axes are identical ($D_{x} = D_{y}$) as expected for a disk-shaped particle. Experimentally, the translational drag coefficient is estimated by measuring the metavehicles’ average drift speed $v_{drift}$, as a function of tilt angle $\theta$ when placing the sample cell at an inclined angle. In this geometry, the projection of the gravitational force and buoyance force ($F_{bulk}$) along the tilted interface is balanced by the translational drag force and the coefficient can be found as $\gamma_{x} = \frac{\mu_m}{c} (v_{drift} - \sqrt{2D_{x}/\tau_{max}x})$ (Supplementary Fig. 8). This corresponds to $D_{x} \approx 0.0088 \text{m}^2/\text{s}$. Similarly, the rotational drag coefficient can be experimentally estimated from measurements on symmetrically shaped vehicles that continuously rotate around their own axis in circularly polarized light (Supplementary Fig. 7c). The driving optical torque $\tau$ (Fig. 2b) is here balanced by the dissipative rotational drag torque ($\tau_{R} = \mu_{rot} \Omega$) to produce a steady-state angular velocity of $\Omega = \frac{k_B T}{D_T} \approx \frac{1}{4} \eta (s_{x \text{net}})$.

Using $\Omega = 10^{-18} \text{J s}$ the model predicts a rotation frequency power dependence similar to that of the measured one. The same rotational drag coefficient, and subsequently power-dependent turn speed, is assumed to be valid also for the translating metavehicles. This corresponds to a rotational diffusion coefficient $D_{\omega} \approx 0.00075 \text{rad}^2/\text{s}$. As both the translational and rotational diffusion coefficients are very small, the equations of motion can be considered deterministic for the purposes of this work (see Supplementary Video 10 for an example of a particle performing stochastic motion in the absence of laser light). The seemingly random variations in speed and angle seen experimentally are thus not primarily due to Brownian fluctuations, but are rather caused by random variations in metavehicle–substrate interactions as the particle travels across the surface (Supplementary Fig. 6).
Owing to the metasurface’s anisotropic response for orthogonal linear polarization directions, a metahelix is propelled by light polarized along its x axis but not along its y axis. Hence, $F_y$ varies with the strength of the polarization component that currently aligns with the x axis, that is, between the maximal force according to equation (2) at perfect alignment and ~0 at orthogonal polarization. Simultaneously, $r$, is proportional to the misalignment angle $\phi$ between the x axis and the polarization direction and increases up to an angle [$\phi$ = 45°] and then decreases again, as seen in Fig. 2b.

For eccentrically polarized light, the metavehicles experience a constant but reduced propulsion force as this light excites both metasurface axes simultaneously, one that generates a driving force (along x) and one that is non-propelling (along y). In a first approximation in which the limited propulsion along the metasurface’s short axis is neglected, this results in a time-averaged driving force that is 50% of the aligned linearly polarized case, because the circularly polarized light can be decomposed into two orthogonal linear components (along x and y). Moreover, $r$, is independent of orientation and the metavehicle experiences a continuous torque proportional to the light intensity (equation (5)), which results in circular trajectories. The radius of curvature of a trajectory is determined by $R_T = \frac{\tau}{\gamma} = \frac{\alpha}{2\gamma}$. $R_T$ is independent of the laser power as the metavehicle’s translational and rotational speed both scale linearly with light intensity, but depends on the ratio between the translational and rotational drag coefficients and on the force–torque ratio, which in turn depends on the metasurface optical properties.

Simulations. Electrodynamics simulations of the metasurface optical properties were performed with a finite-difference time-domain method using commercial software (Lumerical). Transmission and reflection spectra of diffraction orders and SAM densities were obtained using a normally incident linearly polarized plane-wave source and in-plane periodic boundary conditions. Polycrystalline silicon was modelled with a constant real-valued refractive index $n_{si} = 3.45$ as absorption is negligible at the design wavelength ($\text{Im}({\varepsilon_{si}}) < 0.003$). Maximization of the diffraction asymmetry was done with the use of a built-in particle swarm optimization algorithm using 50 generations and a population of 20 for each generation. The free parameters for this optimization were the antenna lengths and unit cell size, whereas the remaining parameters were fixed by fabrication constraints.

Computational fluid dynamics simulations to estimate the translational drag coefficient of a metahelix near a glass–water interface were performed using COMSOL Multiphysics. The simulation environment utilized the laminar flow approximation and consisted of a 200 mm bounding region. An inlet and outlet were placed on the external $xy$ planes with a flow velocity $u_z = 10\text{ m s}^{-1}$ directed along the x axis, whereas all other boundaries were set as sliding walls with velocity $u_z = 0$. To establish a uniform background fluid-flow profile in the metahelix’s frame of reference, the metavehicle was created in the centre of the $xy$ plane with a variable separation distance from the lower $xy$ bounding plane. All the surfaces of the metavehicle were specified as no-slip boundaries. A local high-density mesh region that extended to twice the thickness from the metavehicle was used to resolve the flow. The free stream velocity to obtain the translational drag coefficient.

Fabrication. The metavehicles were fabricated using a top-down approach with dual exposure EBL and subsequent etching of a sacrificial substrate. As illustrated in Supplementary Fig. 3, the fabrication was initiated by depositing amorphous silicon by low-pressure chemical vapour deposition on 400-nm-thick thermally grown SiO$_2$ on a 4-inch (~100 mm) Si wafer. The amorphous silicon was then annealed for 30 min at 1,000 ℃ in an inert atmosphere, which resulted in a polycrystalline Si film 460 nm in thickness. An EBL step was performed to define the metasurface features in a negative resist mask (ma-N 2403 baked at 90 ℃ for 90 s, exposed at 380 µW cm$^{-2}$ with a current of 100 nA, and developed for 6 min). The pattern could then be transferred to the poly-Si by reactive ion etching with HBr (80 sccm HBr, 2 mtorr and 500/250 W of power on the inductively coupled plasma and forward power electrodes, respectively). The remaining resist mask was removed by oxygen plasma stripping (10 min at 10 sccm O$_2$, 200 mtorr, 250 W).

The poly-Si metasurface was then covered by a 600 nm SiO$_2$ layer deposited using plasma-enhanced chemical vapour deposition (400 sccm 2% SiH$_4$, and 1,240 sccm N$_2$, 500 mtorr, 300 ℃). A second EBL step was performed to expose the metasurface shape in a positive resist mask (ARP6200.13 spun at 1,000 r.p.m. and baked at 160℃ for 90 s, exposed at 1,200 µW cm$^{-2}$ with a current of 100 nA, and developed for 12 min), which was then used to lift off the superfluous Ni deposited as a mask for the subsequent etch step. Next, the metavehicles were excavated using reactive ion etching, in which both the exposed plasma-enhanced chemical vapour deposited and thermal SiO$_2$ were removed (10 sccm CHF$_3$, and 15 sccm Ar, 5 mtorr, 600/20 W ICP/FW). This left the metavehicles attached to the Si wafer. To release the metavehicles in water, they were subsequently sonicated in deionized water to release the metavehicles from the substrate and disperse them in solution.

Experimental optimization of the metasurface optical properties was performed using samples produced on transparent 4-inch fused silica wafers but not released into solution (fabrication steps 1–3 in Supplementary Fig. 1). A range of 100 x 100 µm$^2$ metasurfaces with meta-atoms of varying dimensions around the simulated optimum was investigated to refine the experimental diffraction asymmetry. Supplementary Fig. 2a displays the asymmetric transmission figure of merit (FoM = $\frac{1 + T_{\gamma} - 1}{1 + T_{\gamma} + 1}$) where $T_{\gamma}$ are the transmission values to the ±1 diffraction orders and $T_{\gamma}$ is the background transmission, as extracted from Fourier microscopy for all the investigated meta-atom sizes. Supplementary Fig. 2b displays transmission electron microscopy image and a statistical summary of the experimental variation of the critical metaatom dimensions ($L_x$, $L_y$, W and g) for the optimal structures.

Optical measurements. The optical characterization set-up is illustrated in Supplementary Fig. 4. Metasurfaces were illuminated with linearly polarized, quasi-monochromatic and collimated 1,064 nm light at normal incidence. The transmitted light was collected using a water immersion objective with a high numerical aperture and then projected on a Fourier plane to allow for quantification of the polarization-dependent diffraction and overall transmission efficiency.

The optical actuation of metavehicles in water was achieved using 1,064 nm laser illumination with measured temporal power fluctuations of ±1% over 1 h. The illuminated area had a Gaussian intensity profile with a beam diameter of ~400 µm (full-width at half-maximum) and a divergence angle of ~1.4° at the sample, which thus approximates a plane wave within the microscope field of view. To avoid the large intensity variations at the periphery of the illuminated area, the metavehicles were confined to move within the central circular area of the beam (~150 µm). Here, any local intensity deviates less than ~15% from the average intensity (given in Figs. 3 and 4). A quarter-wave and half-wave plates allowed the polarization state to be changed between linearly polarized at an arbitrary direction or circularly polarized with either right or left handedness. The linear polarization ratio was ~100:1, whereas the intensity ratio between the semi-major and semi-minor axes of the polarization ellipse for the circularly polarized light was ~0.9:1 for both handednesses.

Measurements were performed using an about 4 µl sample cell formed by two microscope slides separated by a 120 µm spacer. The microscope slides were made hydrophilic by cleaning in 2 wt% Hellmanex III heated to 70 ℃ for 15 min to prevent the metavehicles from sticking to the glass substrate. Video tracking analysis allowed for quantification of the metavehicle position and orientation changes.

Data availability
The datasets analysed during the current study can be downloaded from https://doi.org/10.6084/m9.figshare.14270783. The data will be available after an embargo period of six months, which starts from the final publication date of the manuscript.

Code availability
The codes used during the current study are available from the corresponding author on reasonable request.

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Author contributions
M.K. and D.A. conceived the study. D.A. manufactured samples, performed experiments and analysed data. D.G.B. performed the electrodynamics simulations and optimization. S.J. performed the hydrodynamic simulations. D.A., M.K. and D.G.B. wrote the paper with input from all the authors.

Competing interests
The authors declare no competing interests.

Additional information
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