Opto-thermoelectric microswimmers

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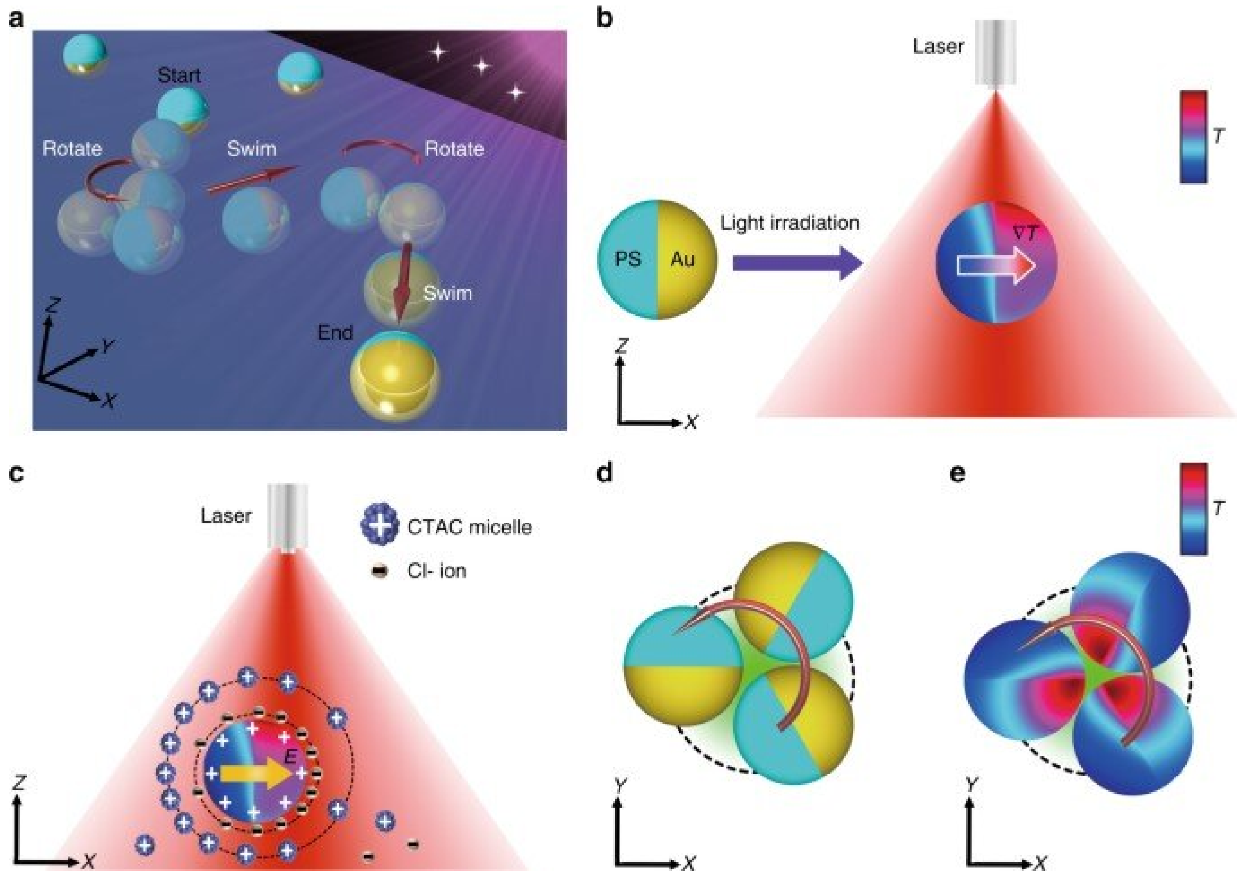


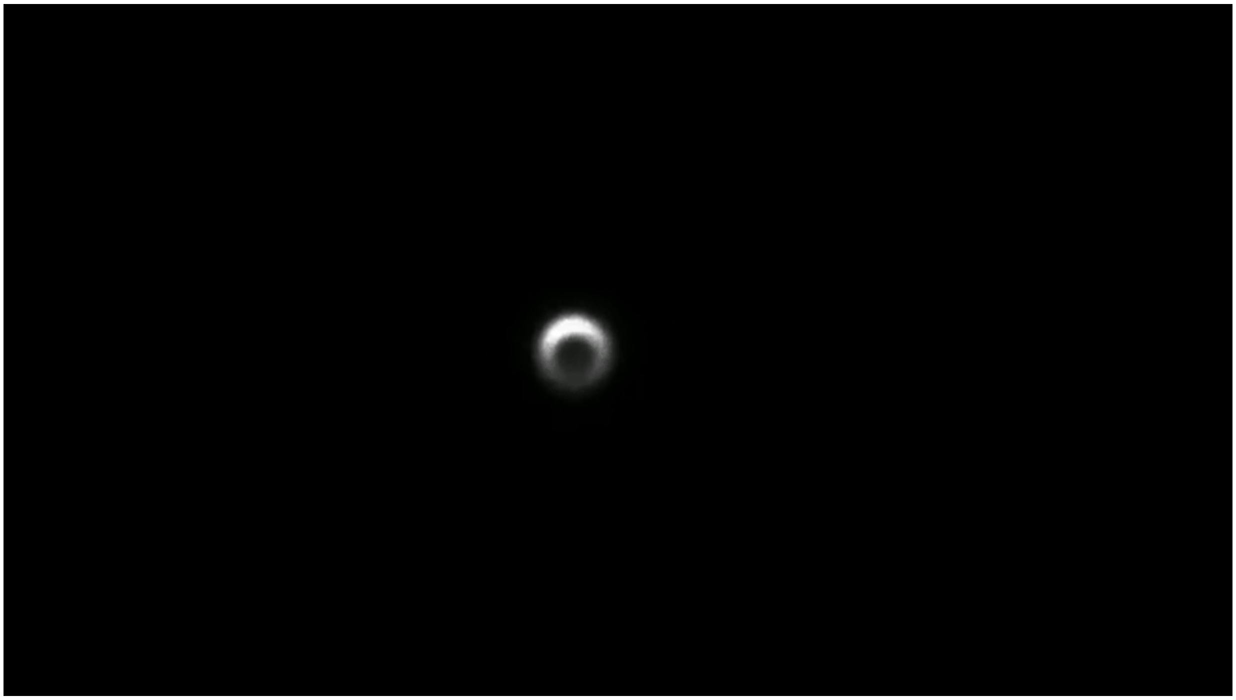
Conceptual design for optical driving and steering of opto-thermoelectric microswimmers. (a) Under light fields, PS/Au Janus particles are set to swim and rotate alternatively to follow a predefined path. (b) Upon light irradiation on a Janus particle, a temperature gradient ∇T pointing from the PS side to the Au side is generated on the particle surface due to the asymmetric absorption of PS and Au. (c) Once the Janus particle is dispersed in a 0.2 mM CTAC solution, a thermoelectric field is induced to drive the Janus particle along the temperature gradient. The white “+” symbols indicate the positively charged surface. In b, c, the asymmetric heating and thermoelectric field under a defocused laser beam are shown in the X–Z plane. (d) Schematic illustration and e asymmetric heating of the Janus particle when set to rotate (as shown by the maroon arrow) in the X–Y plane by another focused laser beam (indicated by the green region surrounded by a dashed circle). In d, e, the defocused laser beam is switched off Credit: Light: Science & Applications, doi: 10.1038/s41377-020-00378-5

In a recent report, Xiaolei Peng and a team of scientists in materials science and engineering at the University of Texas, U.S., and the Tsinghua University, China, developed opto-thermoelectric microswimmers bioinspired by the motion behaviors of Escherichia coli (E. coli). They engineered the microswimmers using dielectric gold Janus particles driven by a self-sustained electric field arising from the optothermal response of the particles. When they illuminated the constructs with a laser beam, the Janus particles showed an optically generated temperature gradient along the particle surfaces, forming an opto-thermoelectrical field to propel themselves along.

The team discovered the swimming direction of microswimmers based on the orientation of the particle. They proposed a new optomechanical approach to understand the navigation direction of microswimmers that relied on a temperature-gradient-induced electric field, using a focused laser beam. By timing the second rotation laser beam in the setup, they positioned the particles at any desired orientation to efficiently control the swimming direction. Using dark-field optical imaging and a feedback control algorithm the scientists facilitated automated microswimmer propulsion. The opto-thermoelectric microswimmers will have applications in colloidal systems, targeted drug delivery and biomedical sensing. The research is now published in *Nature Light: Science & Applications*.

Microswimmers

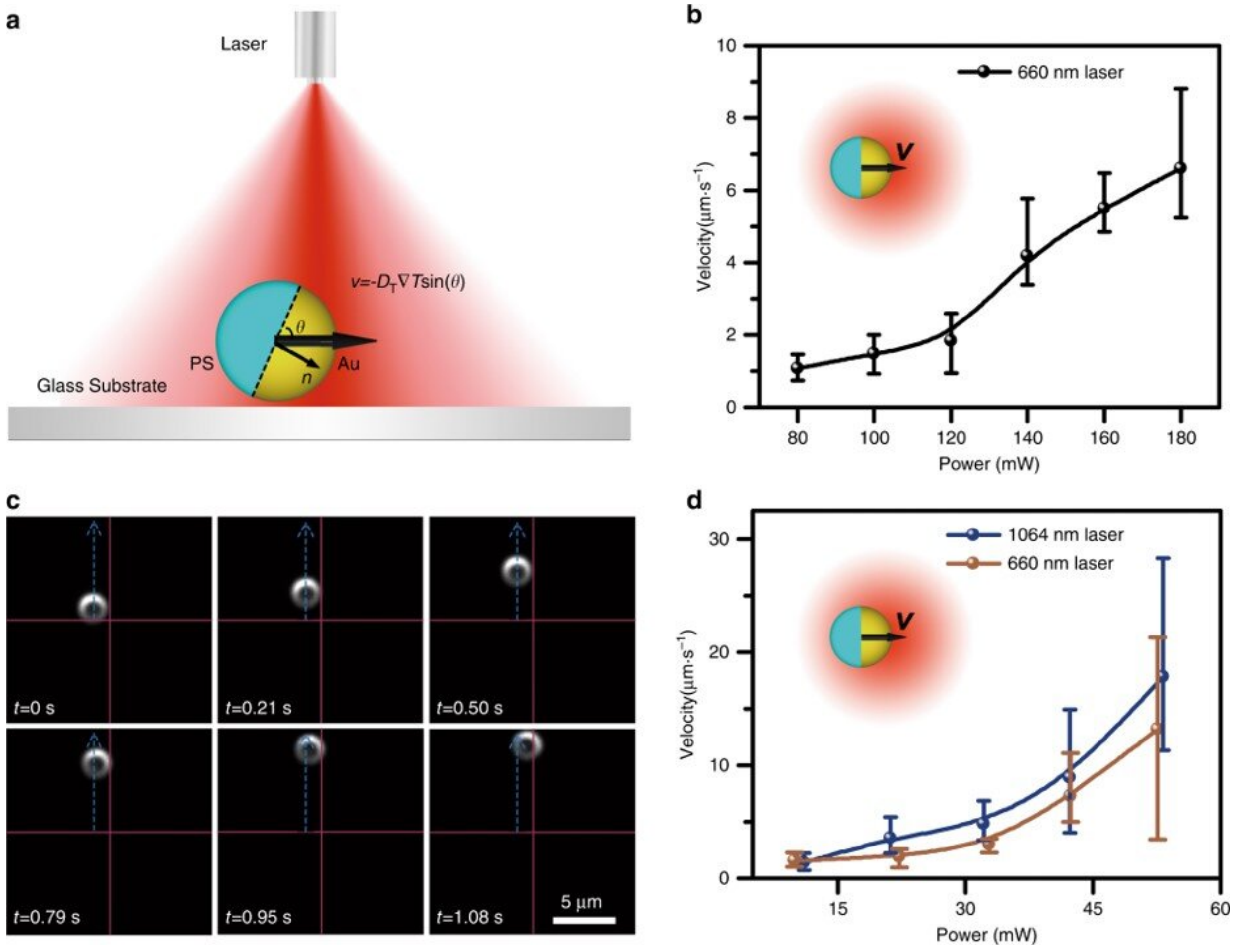
Microswimmers are a class of micromachines that can convert external chemical, acoustic or electromagnetic energy into swimming motion. Such machines can be used for diverse biomedical applications ranging from targeted drug delivery to precision nano-surgery and diagnostic sensing. In this work, Peng et al. used all-optical microswimmers based on Janus particles in an optothermally generated electric field to build opto-thermoelectric microswimmers that mimicked the 'run-and-tumble' motion of E. coli cells. In its mechanism of action, the asymmetric light absorption of a Janus particle under laser beam irradiation caused a self-generated temperature gradient for a resulting opto-thermoelectric field that propelled the particle along. The scientists drove the process using two laser beams, where the second focused laser beam triggered the in-plane rotation of individual Janus particles under optical heating. The team achieved stable particle rotation due to the thermoelectric force, optical force and stokes drag force in the setup. Peng et al. further investigated the working mechanisms by coupling experiments with theory and simulations.



A swimming 2.1 µm PS/Au Janus particle in 0.2 mM CTAC (cetyltrimethylammonium chloride) solution. Credit: Light: Science & Applications, doi: 10.1038/s41377-020-00378-5

Concept and Design

To facilitate photon-to-phonon (light to sound) energy conversion, the team developed opto-thermoelectric swimmers by half-coating a thin gold (Au) layer on the surface of polystyrene (PS) beads. Upon light irradiation, the absorption difference between PS and Au created a temperature gradient on the PS/Au Janus particle surface. Peng et al. dispersed the Janus particles into a water solution to convert the thermal energy to mechanical energy. When driven by the thermoelectric field and irradiated by a laser beam, the Janus particles migrated along the PS-to-Au direction to demonstrate the swimming state. However, thermal fluctuations could change the orientations of Janus particles causing them to drift away from their courses during migration. To maintain the target course, the scientists switched off the defocused laser beam and used a focused laser beam to rotate and trap Janus particles for reorientation. Upon reaching their destined orientation, they turned off the focused laser beam and reverted the Janus particles to the defocused laser beam to bring them back to the swimming state. This two-state switching process provided the best possible design to actively navigate microswimmers for a variety of functionalities.

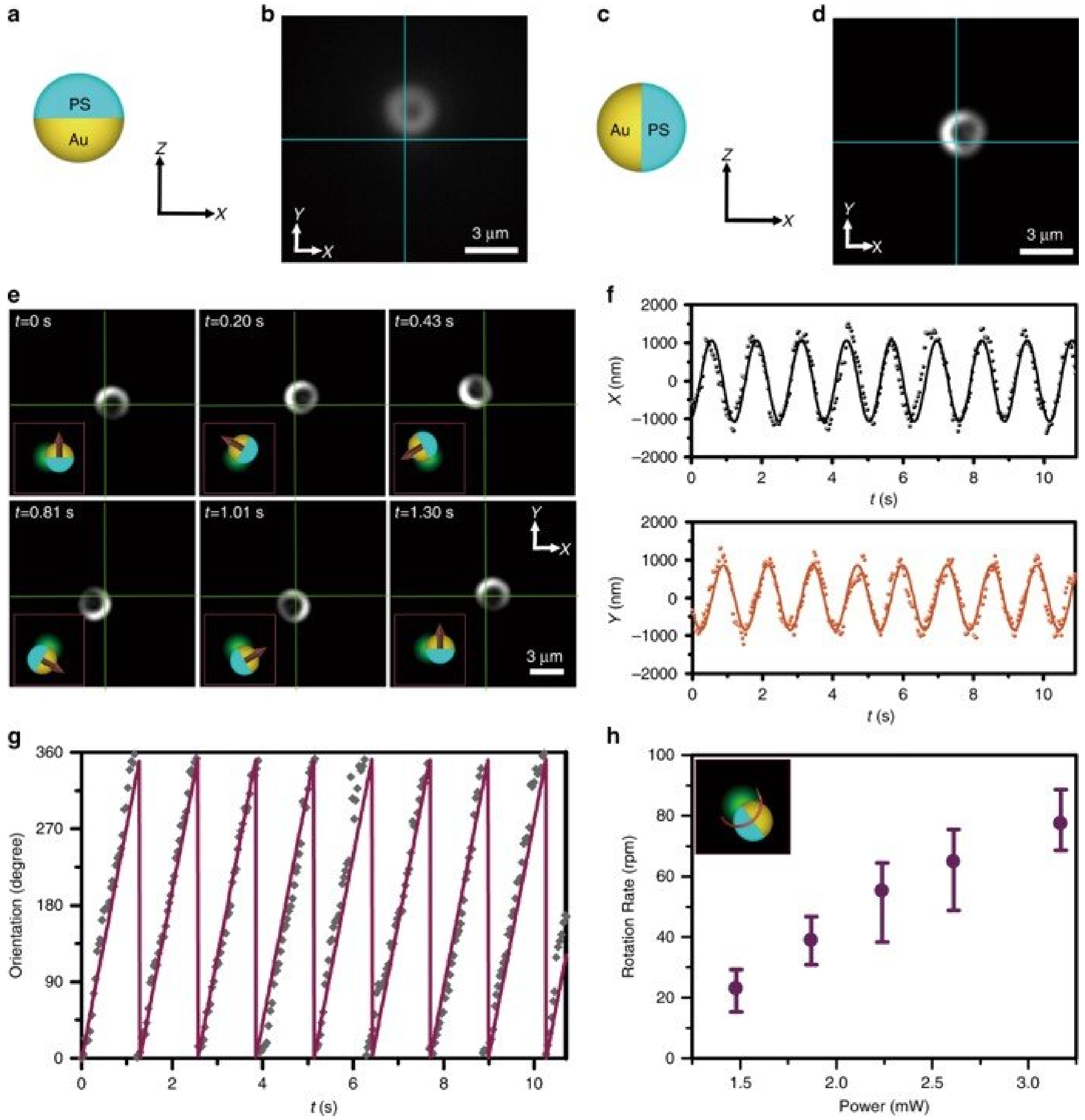


Opto-thermoelectric swimming of PS/Au Janus particles under a defocused laser beam. (a) Schematic illustration of the swimming mechanism. The velocity is directed from the PS hemisphere to the Au-coated hemisphere. (b) Swimming velocity as a function of the optical power for 5 µm PS/Au Janus particles. A 660 nm laser beam with a beam size of 31 µm was applied to drive the swimming. (c) Time-resolved images of a swimming 2.1 µm PS/Au particle. A 1064 nm laser beam with a beam size of 31 µm and a power of 32 mW was applied to drive the swimming. (d) Swimming velocity as a function of the optical power for 2.1 µm PS/Au Janus particles. Two different laser beams, i.e., a 1064 nm laser beam with a beam size of 45 µm and a 660 nm laser beam with a beam size of 45 µm, were applied to drive the swimming. The insets of b, d show a PS/Au Janus particle driven to swim under a defocused laser beam. All the aforementioned beam sizes were obtained by experimental measurement. Credit: Light: Science & Applications, doi: 10.1038/s41377-020-00378-5

Opto-thermoelectric swimming and orientation control

When Peng et al. used a defocused laser beam for directed motion of opto-thermoelectric microswimmers, they achieved an "energy pool" for the Janus particles. They named the motion along the self-generated temperature gradient as self-thermophoresis. In the surrounding solution of cetyltrimethylammonium chloride (CTAC), self-thermophoresis arose from thermoelectric effects to enable the characteristic motion of the particles. The team could reduce the chamber thickness of the experimental setup to stabilize the fluidic flow and facilitate the directional transport of Janus particles. Since the orientation of Janus particles could be randomly changed through thermal fluctuations, the team used a second focused laser beam to achieve particle rotation to efficiently navigate the swimming direction. They accomplished this by switching laser beams to quantitatively analyze the rotating Janus particle and extract their real-time position, as well as orientation data.

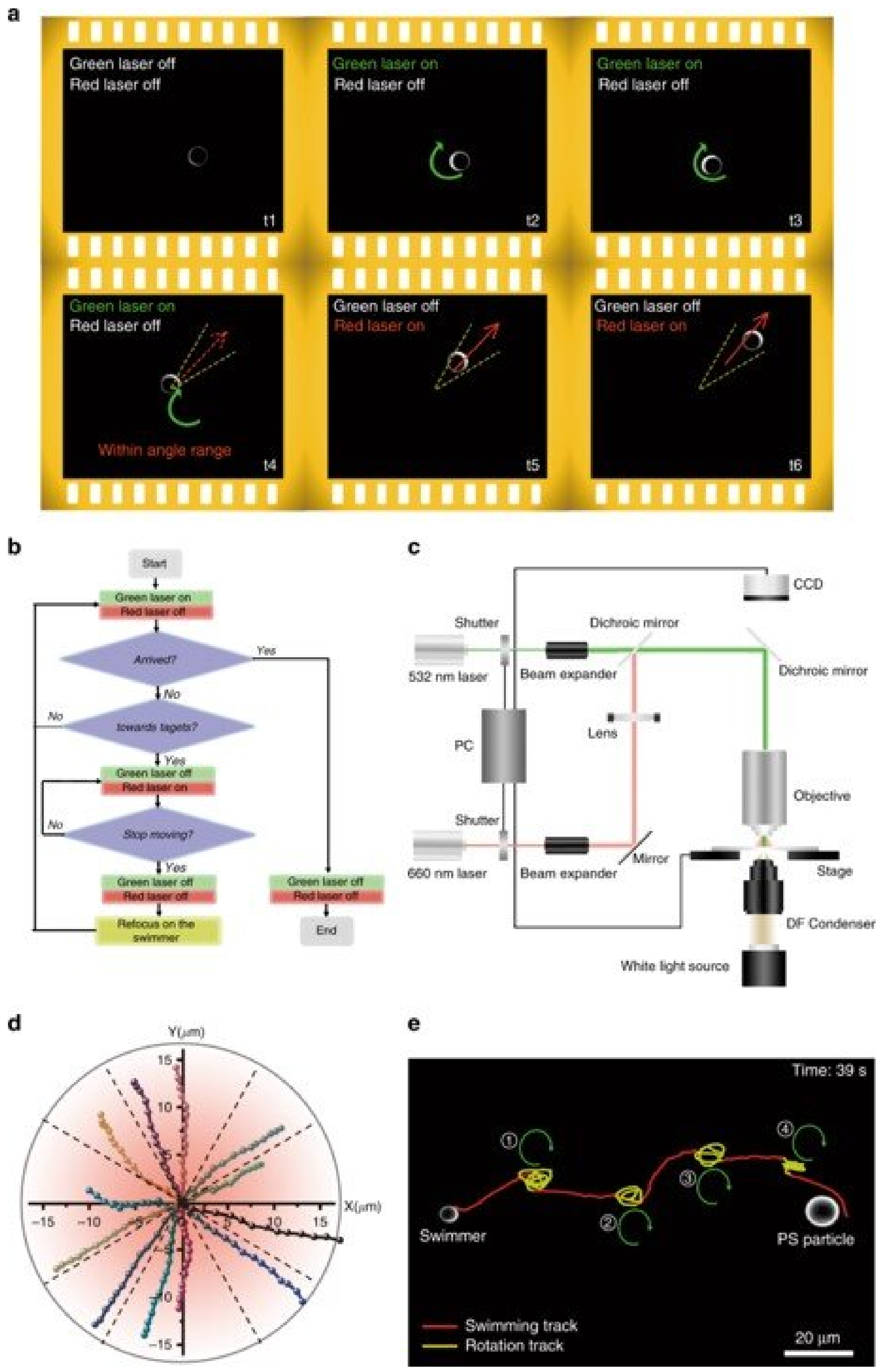
When the laser power increased, the particle rotation also increased, although continued increase of laser power caused strong heating effects and thermal damage to the Janus particle. The rotational speed was dependent on the particle size. To understand the thermoelectric force, Peng et al. simulated the temperature distribution on the surfaces of PS/Au Janus particles. Then they calculated the thermoelectric force and optical force to understand the rotation dynamics. The team conducted further investigations to understand the self-alignment behavior of the Janus particle.



Orientation control of PS/Au Janus particles with a focused laser beam. (a) Configuration and (b) corresponding dark-field image of a free 2.7 µm PS/Au Janus particle in the X–Z plane. (c) Configuration and (d) corresponding dark-field image of a rotating 2.7 µm PS/Au Janus particle in the X–Z plane. (e) Time-resolved dark-field images of the rotation of a 2.7 µm PS/Au Janus particle. The half-cyan, half-golden particles in the insets illustrate the corresponding configurations, while the maroon arrows in the insets illustrate the orientations. The green spot in the insets represents the laser beam (with a wavelength of 532 nm). (f) Displacement of the centre of the 2.7 µm Janus particle as a function of time. The centre of the beam is set as the origin of the coordinates. The fitting sinusoidal curves indicate a circular rotation. (g) Orientation evolution of the 2.7 µm Janus particle as a function of time. The fitting sawtooth wave indicates a consistent steering of the orientation. (h) Rotational rate as a function of the optical power for 2.7 µm PS/Au Janus particles. In a–d, for a free Janus particle, no boundary at the particle hemisphere was observed in the dark-field optical image because the Au-coated part tended to align with the direction of gravity. In contrast, when in-plane rotation of the Janus particle was initiated, the PS-Au interface became perpendicular to the substrate due to the coordinated effect of the thermoelectric force and the optical force. An asymmetric ring was observed in the dark-field optical image, with the brighter half-ring corresponding to the Au coating owing to its stronger optical scattering. The inset illustrates the rotation under a green laser beam (with a wavelength of 532 nm). The laser beam size on the sample plane is 2.65 µm for e, h. A power of 1.9 mW was applied for rotation in (e) Orientation control of PS/Au Janus particles with a focused laser beam. Credit: Light: Science & Applications, doi: 10.1038/s41377-020-00378-5

Feedback control method

The team then established a feedback algorithm to facilitate active navigation and steer the swimming direction of Janus particles. To accomplish closed-loop control, they developed a computer program to track the real-time position and orientation of a given Janus particle and automatically coordinated the control system. In the experimental setup, two computer-controlled shutters dictated the on/off states of two individual laser beams. The scientists successfully drove the directional swimming of Janus particles, where an increase in rotation speed reduced the control accuracy of the swimming direction. To account for this, Peng et al. used a higher-frame-rate charged-coupled device (CCD) camera to significantly improve the accuracy of feedback control. They then demonstrated active navigation of the PS/Au Janus particles using the feedback control algorithm for targeted transportation of opto-thermoelectric swimmers. The work indicated the potential of opto-thermoelectric microswimmers to carry drug molecules and non-metallic parts for precise delivery with potential applications in targeted nano/micro-drug delivery.



Directional swimming and targeted transportation of PS/Au Janus particles with a feedback control method. (a) Schematic illustration of directional swimming with feedback control on the experimentally recorded images, where a focused green laser beam and a defocused red laser beam were employed for navigating and driving the swimming, respectively. (b) Flow chart of the feedback control method. (c) Optical setup and mechanical layout for the feedback control method. (d) Trajectories of 5 µm PS/Au Janus particles swimming in different directions. (e) Targeted delivery of a 5 µm PS/Au Janus particle to a 10 µm PS particle. A 5 µm 532 nm laser beam with a power of 2.6 mW was used to drive the rotation, while a 660 nm laser beam with a beam size of 31 µm and a power of 160–200 mW was applied to drive the swimming. Credit: Light: Science & Applications, doi: 10.1038/s41377-020-00378-5

In this way, Xiaolei Peng and colleagues developed opto-thermoelectric microswimmers with all-optical actuation and navigation. They accomplished this by harnessing opto-thermoelectrical coupling of the Janus particles. The heat generated by the light-irradiated Janus particles created a thermoelectric field to propel the particles in a specific direction without chemical fuel. They used a focused laser beam to steer the orientation of the microswimmers and controlled the rotation of Janus particles with a second beam. The mechanism can be further explored to develop intelligent microrobots for multiple tasks in biomedicine.

More information: 1. Peng X. et al. Opto-thermoelectric microswimmers, *Nature Light: Science & Applications*, doi.org/10.1038/s41377-020-00378-5
2. Esteban-Fernández de Ávila B. et al. Single cell real-time miRNAs sensing based on nanomotors. *ACS Nano*, doi.org/10.1021/acsnano.5b02807
3. Kim K. et al. Ultrahigh-speed rotating nanoelectromechanical system devices assembled from nanoscale building blocks. *Nature Communications*, 10.1038/ncomms4632

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