Miniaturized robots can be propelled through biological fluids by an enzymatic reaction or ultrasound

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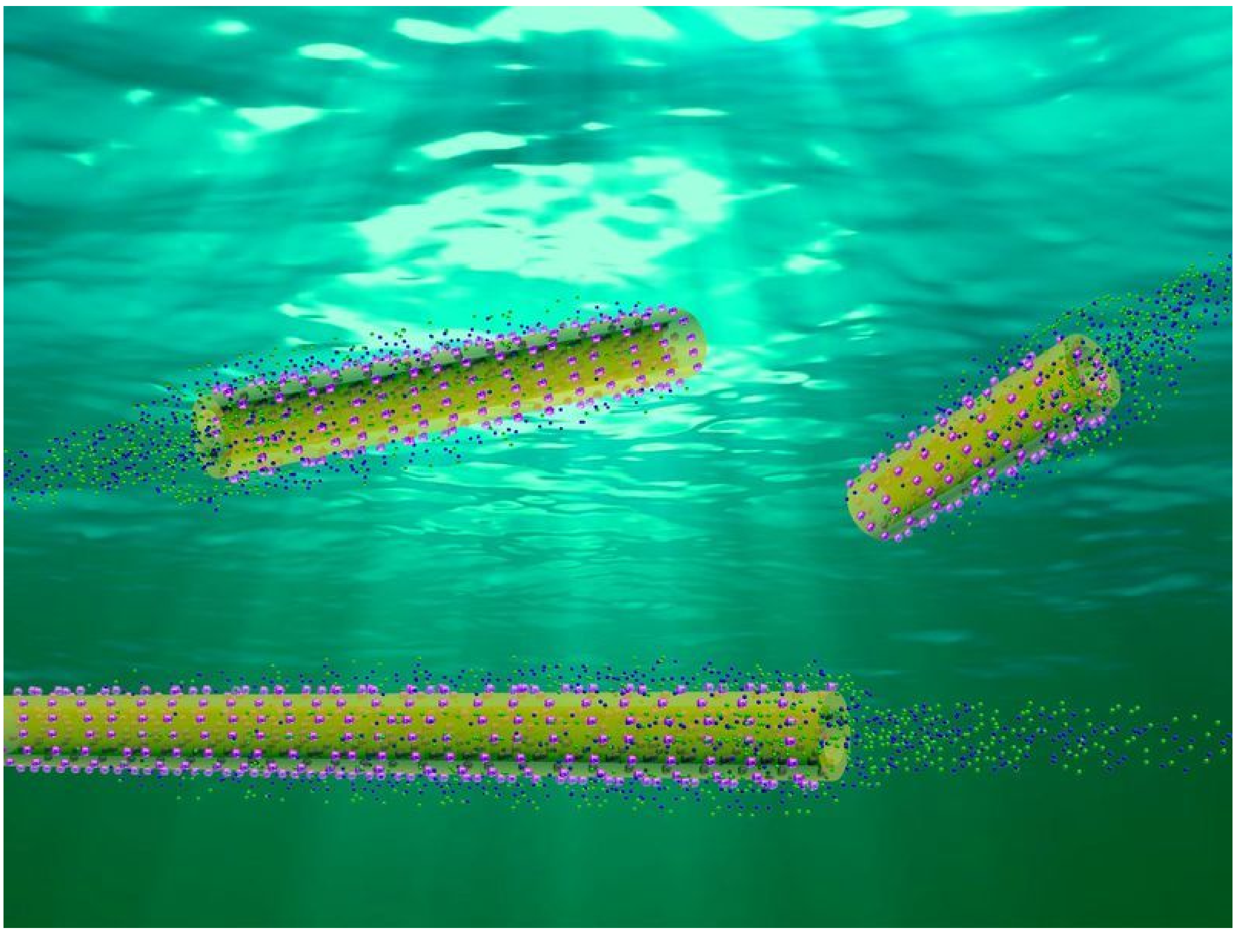


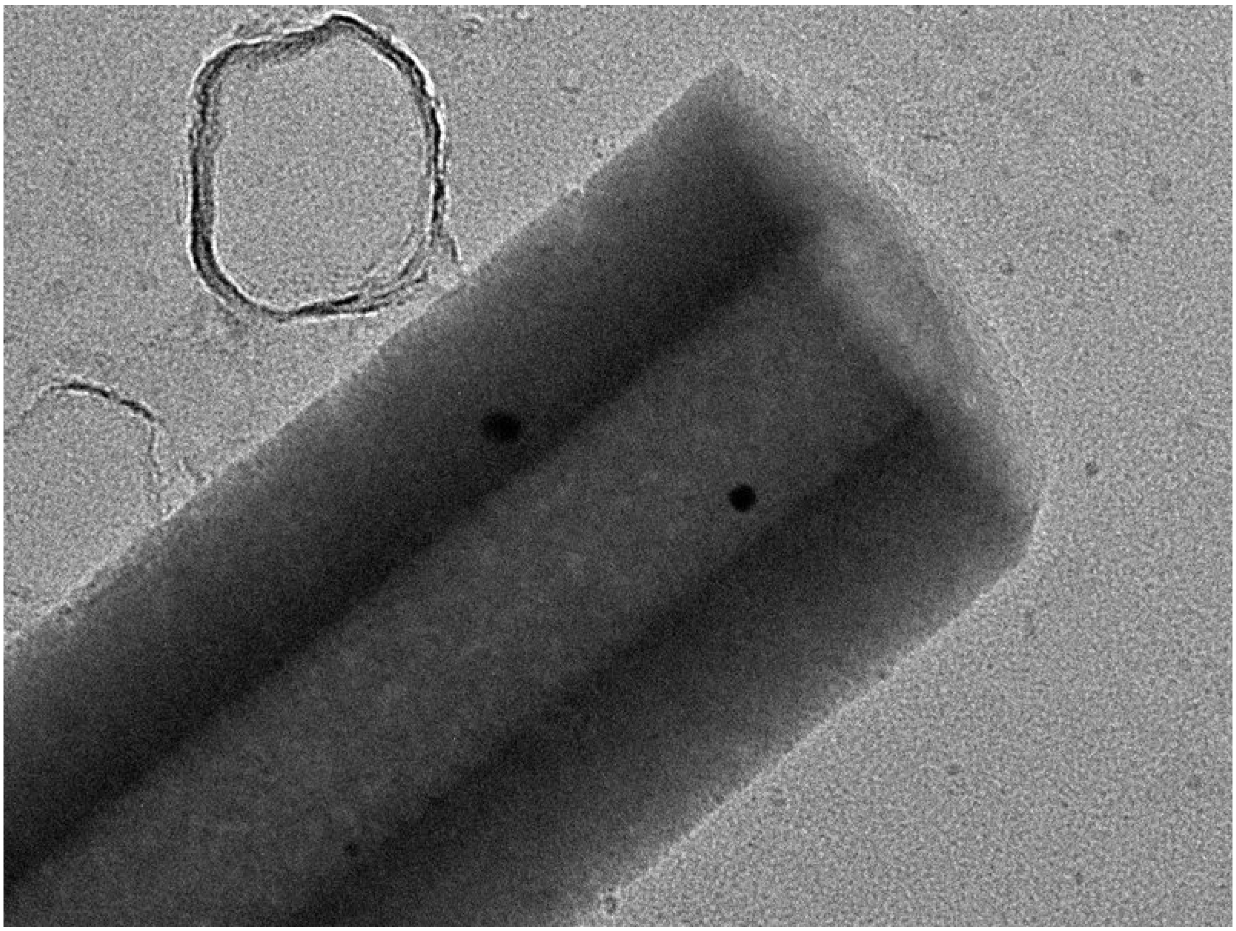
An enzyme-propelled nanorobot: urease-coated nanotubes turn into a propulsion system in a urea-containing liquid because the enzyme breaks down the urea into gaseous products. Since the tubes always have small asymmetries, the reaction products generate a current in the fluid which propels them out of the tube like a jet. Credit: MPI for Intelligent Systems

Nanorobots and other mini-vehicles might be able to perform important services in medicine one day – for example, by conducting remotely-controlled operations or transporting pharmaceutical agents to a desired location in the body. However, to date it has been hard to steer such micro- and nanoswimmers accurately through biological fluids such as blood, synovial fluid or the inside of the eyeball. Researchers at the Max Planck Institute for Intelligent Systems in Stuttgart are now presenting two new approaches for constructing propulsion systems for tiny floating bodies. In the case of one motor, the propulsion is generated by bubbles which are caused to oscillate by ultrasound. With the other, a current caused by the product of an enzymatic reaction propels a nanoswimmer.

Jet aircraft have led the way. They burn fuel, eject the combustion products in one direction and as a result move in the opposite direction. Researchers at the Max Planck Institute for Intelligent Systems in Stuttgart do it in a very similar way - albeit on a much smaller scale. Their underwater-nanorobot is a single-walled nanotube made of silicon dioxide, a mere 220 nanometres (billionths of a metre) in diameter. A particle of that nature would not normally be able to propel itself in fluids. The scientists therefore coated either only the inner or the inner as well as the outer surface or of the nanotube with the enzyme urease which breaks down urea into ammonia and carbon dioxide.

If a nanotube prepared in this way is introduced into a fluid containing urea, this urea is broken down at the urease-coated internal wall. The reaction products generate a current in the fluid which propels them out of the tube like a jet. As such a nanoswimmer either is thinner at one end than at the other or the the urea is not distributed homogeniously over its surface, this results in a thrust, so that the micro-swimmer experiences propulsion in the opposite direction – as in a jet aeroplane. The nanojets reached speeds of 10 micrometres per second, i.e. almost four centimetres per hour.

The smallest jet engine in the world



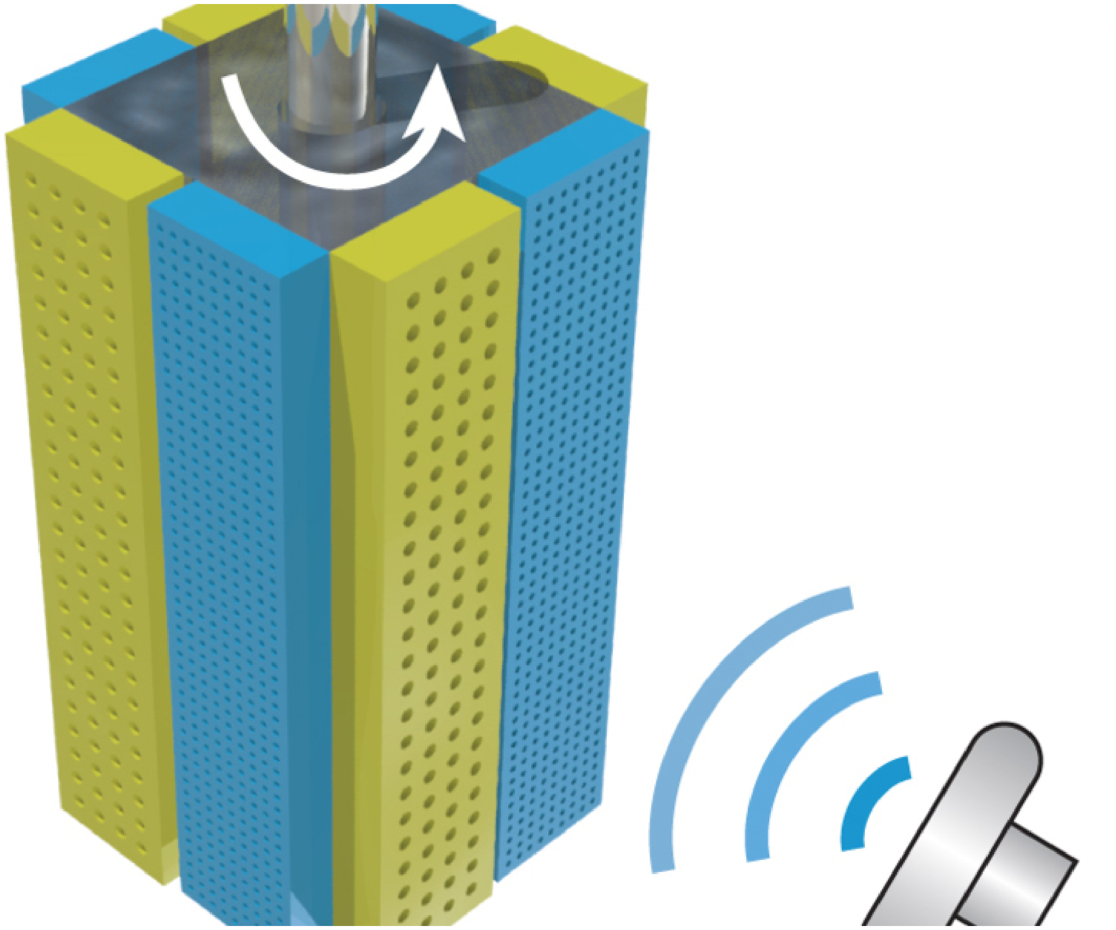
Beating their own record: the tube that Samuel Sanchez and his team of researchers transformed into a tiny jet engine for nanorobots with urease coating has an opening of approx. 220 nanometre – the researchers' previous record, which is still in the Guinness Book of Records, was around three-times bigger. Credit: MPI for Intelligent Systems

Admittedly, coating a nanorobot to achieve a chemical drive is by no means new. However, the tube now presented, with its 220 nanometre opening, represents the smallest jet propulsion system so far constructed in the world. "Our previous record, which is still in the Guinness Book of Records, was around three-times bigger", explains Samual Sanchez who leads the Smart NanoBioDevices Group at the Max Planck Institute for Intelligent Systems in Stuttgart and at the same time holds a professorship at the Institute for Bioengineering of Catalonia in Barcelona.

And there is another new aspect of the nanojet which scientists from the Harbin Institute of Technology in Shenzhen in China also helped to develop: for the first time, all the materials and reaction partners used are fully biocompatible. "Previous chemical drives of this kind were usually based on a metallic catalyst at the surface of which hydrogen peroxide was broken down into hydrogen and oxygen molecules", says Sanchez. Oxygen bubbles are created in the process, which creates a thrust in the opposite direction. Both the hydrogen peroxide and the gas bubbles would have disadvantages if used in the human body. But this is not the case with the urease-coated version with its water-soluble – and therefore bubble-free – reaction products. "Urease occurs anyway in the human organism", Sanchez explains.

The researchers now want to test the biocompatibility more precisely – and in the process examine whether they can succeed in implanting such micro-tubes into individual cells. "That would be necessary, of course, in order to bring drug molecules to their destination, for example", says Sanchez.

Oscillating bubbles provide thrust



Ultrasonic motor for minirobots: the cuboid motor developed by Peer Fischer and his team of researchers is equipped with chambers for bubbles of two different sizes (yellow and blue). The bubbles of one size are located on one-half of the cuboid face divided lengthwise. Ultrasound causes the bubbles to oscillate. The bubbles of different sizes produce differently strong thrusts, so that the cuboid rotates on its own axis. Credit: Tian Qiu/MPI for Intelligent Systems

While gas bubbles were still unwanted in the approach specified, they form the very centrepiece of a entirely new principle of propulsion for minirobos, which colleagues at the Institute in the Micro, Nano and Molecular Systems Group led by Peer Fischer propose. However, here the gas bubbles are not bubbling freely through the fluid and therefore cannot damage the organism. Rather, the researchers enclose the micro-bubbles in small cylindrical chambers along a plastic strip. To provide the drive, therefore, the gas bubbles expand and contract cyclically because ultrasound causes them to oscillate. As the pulsating bubbles are in chambers open on one side, they only expand through this opening. In the process, they exert a force on the opposite wall of the chamber which propels the plastic strip. In order to achieve propulsion worth mentioning, the researchers arranged several chambers with air bubbles in parallel on their polymer strip.

A notable aspect: the sound wave frequency required to cause them to oscillate depends on the size of the tiny bubbles. The bigger the bubbles, the smaller the corresponding resonant frequency. The researchers used this connection to cause their swimmer to rotate alternately clockwise and anti-clockwise. To do so, they placed bubbles of different sizes on the two halves of the four, long cuboid faces divided lengthwise. Two different sound frequencies were then used in a liquid to each cause all the bubbles of one size to oscillate. In this way, the scientists generated thrusts exclusively on one-half of the cuboid face which caused it to rotate on its own axis. This small acoustically driven rotation motor with longitudinal areas each five square millimetres in size achieved up to a thousand rotations per minute in the process.

One possibility for steering mini-swimmers

"The variation in the size of the bubbles thereby enables a mini-swimmer to deliberately steer in different directions", says Tian Qiu, who also conducts research at the Max Planck Institute in Stuttgart and played an appreciable role in the study. According to Qiu, a further benefit of the new principle of propulsion is that even swimmers with a complicated geometric structure can be coated with the wafer-thin strips together with chambers for the bubbles. He goes on to explain that the use of ultrasound is also suited to optically impenetrable media such as blood.

Light waves, which are also a potential control instrument for micro-drives, can achieve nothing in this case. The researchers now want to use tests in real biological media to check whether the new drive principle is also able to make the most of its advantages in practice.

More information: Xing Ma et al. Bubble-Free Propulsion of Ultrasmall Tubular Nanojets Powered by Biocatalytic Reactions, *Journal of the American Chemical Society* (2016). DOI: 10.1021/jacs.6b06857

T. Qiu et al. Wireless actuation with functional acoustic surfaces, *Applied Physics Letters* (2016). DOI: 10.1063/1.4967194

Provided by Max Planck Society

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