Efficient swimmers: Jellyfish move through the water with very little energy. Their propulsion therefore serves as a model for swimming robots.

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MODELED ON A JELLYFISH

TEXT: TIM SCHRÖDER

They're not the most popular of sea creatures, but they set standards in terms of underwater propulsion. A team from the Max Planck Institute for Intelligent Systems in Stuttgart has designed a robot based on the cnidarians, not least because jellyfish swim very efficiently. In the future, jellyfish-bots could help to remove plastic waste from particularly sensitive ecosystems such as coral reefs.

There is something meditative about the way jellyfish slowly pulse through the water, contracting their bell and gliding silently and at a leisurely pace. Their graceful movements have already inspired various research groups around the world to mimic jellyfish in their laboratories. The result is typically an apparatus that makes a lot of noise and whose mechanics consume a relatively large amount of energy. In terms of grace and smoothness, they cannot hold a candle to real jellyfish. But now a team from the Max Planck Institute for Intelligent Systems in Stuttgart has come very close to the model presented by nature. The researchers have constructed a lightweight, silent, economical jellyfish robot that steers through the water with gentle strokes. The jellyfish-bot can cover six centimeters in one second – it may not be lightning fast, but it is a typical speed for a jellyfish.

And the jellyfish-bot can do more than just paddle through the water. In place of a closed bell, the roughly palm-sized device has six arms that can each be controlled individually. This enables it to swim and grasp objects at the same time. "Our aim was to develop a jellyfish robot that we could use to fish plastic waste and other debris out of the ocean," explains robotics expert Tianlu Wang, a postdoctoral researcher who works in Metin Sitti's Physical Intelligence department in Stuttgart. "Obviously, we won't be able to use devices like this to retrieve the many millions of tons of plastic waste from the ocean. Rather, we're thinking of using them in particularly sensitive ecosystems, such as coral reefs." Since the jellyfish-bot travels silently, it does not startle fish and other animals. Swimming tests in the pond behind the Institute building have already demonstrated this. The researchers placed the jellyfish in the water, allowed them to sink a little, and then triggered the swimming movement via remote control. The jellyfish promptly rowed silently back to the surface without disturbing the animals in the pond. The jellyfish-bot is made of lightweight plastic. This makes damaging corals virtually impossible.

At the heart of the jellyfish-bot are so-called Hasel muscles. "Hasel" stands for *hydraulically amplified self-healing electrostatic-actuator*s – quite a mouthful for what is really a straightforward bit of electro-engineering. The Hasel muscles are small plastic bags filled with liquid that are squeezed together under electric voltage, changing their shape in the process. They were developed several years ago by a group led by Christoph Keplinger, the current Managing Di- →

rector at the Stuttgart Institute. Essentially, the bags work according to the capacitor principle. A capacitor is an electrical component consisting of two electrodes separated by an insulating layer, the dielectric. When a voltage is applied to the capacitor, one electrode becomes positively charged, the other negatively charged, creating an electric field between the two electrodes separated by the dielectric. The researchers take advantage of this effect in the Hasel muscles. The plastic bags are covered on both sides with a very thin electrode. The liquid inside of them serves as an insulating dielectric. Under voltage, the positively and negatively charged electrodes attract each other like the opposite poles of two magnets – and the soft little bag is squeezed together. The challenge is to design the bags in such a way that they perform precisely defined movements when the field is switched on and off.

In the case of the jellyfish-bot, this works perfectly. The arms of the jellyfish-bot consist of several segments that are flexibly connected to each other. Each of these segments is equipped with a Hasel muscle. If the researchers apply a voltage, the muscles contract and bend the jellyfish arm like a finger. By rhythmically switching on and off, the arm stretches and bends – the perfect swimming motion!

"The only issue was that Hasel muscles had never been used underwater before," says Wang's colleague Hyeong-Joon Joo, who works in the Robotic Materials department. "That meant we first had to make the electronics watertight." Hyeong-Joon Joo opted for common and, most importantly, cheap materials – the crucial requirement for the robots actually being put to use in the future. For example, he wrapped the jellyfish-bot's arms and inner workings in film made of PET, a common synthetic polymer often used for plastic bottles. For the dielectric fluid in the Hasel muscles, he uses silicone oil. In the future, different materials could be used to increase the robustness and service life of the robot. Biodegradable substances could also be used.

Film sandwich with electric drive

Altogether, the jellyfish-bot consists of several layers: A film that gives the arms rigidity and ensures that they extend again when the electric field is switched off; the flexible electrodes; the polymer films that encase the liquid dielectric; and the waterproof PET film. In addition, the middle of the jellyfish contains small floating bodies and a small weight that keeps the jellyfish upright like a weeble-wobble. In most experiments, the researchers

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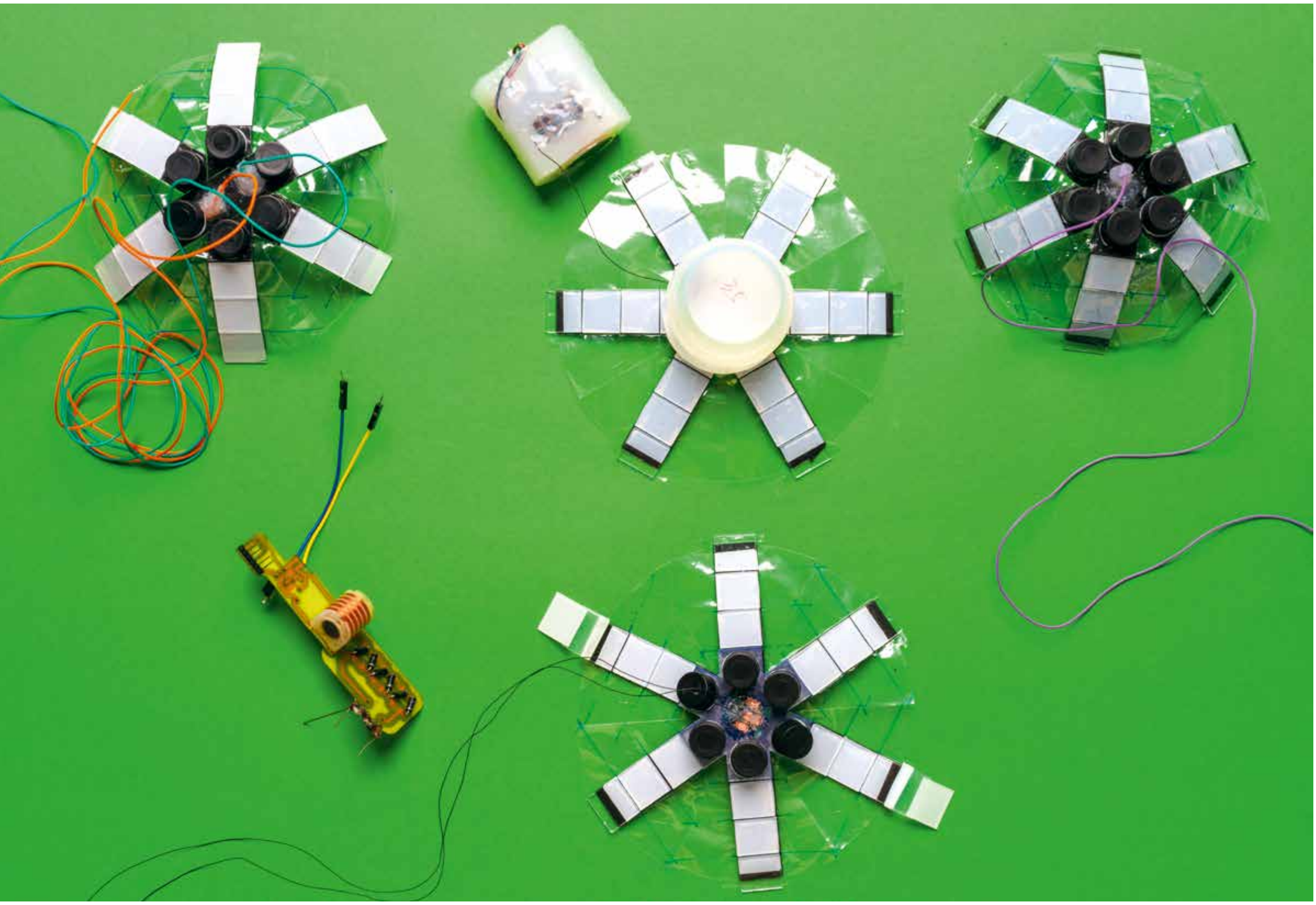
Combined competence: Robotics experts Tianlu Wang (left) and Hyeong-Joon Joo, who have further developed the artificial Hasel muscles for underwater use, among other things, have made the jellyfish-bot swim.



Robot zoo: The Stuttgart team has developed various versions of a jellyfish robot. In the basic version, all arms are controlled together (top right). In two further developments, the arms are controlled in two groups (top left and bottom middle) – some of the tentacles can be used for swimming and some for gripping. For control via cables, the researchers use external electronics (bottom left), but the jellyfish-bot can also be navigated wirelessly (top center).

SUMMARY

With the help of Hasel muscles, a robot – a jellyfish-bot – can swim in an energy-efficient manner, similar to a real jellyfish.

Because jellyfish-bots are made of soft components and are powered silently, they could be well suited for picking up plastic debris in particularly fragile ecosystems such as coral reefs and mangrove forests, or for taking marine biology samples.

supplied the jellyfish robots with power and controlled them via cables, because the on-board battery only allows very short swimming trips.

It took a lot to get this film sandwich to float, says Tianlu Wang, who was responsible for the electrical engineering. For instance, it was not enough to simply install a capacitor; when the current is switched off, a capacitor does not fully discharge immediately. This means that the arms do not fully extend right away. If you simply switch a capacitor on and off, the movement ends in a convulsive tremor. As a result, additional resistors had to be installed in the jellyfish to allow the capacitor to discharge quickly. One of the biggest challenges, however, was to put the jellyfish-bot, which is only 16 centimeters wide, under high voltage. That's because to generate an electric field strong enough to compress the liquid-filled bags, a voltage of around 10 kilovolts is needed – a value more commonly found in the motors of electric cars and scooters. "We had to customize everything perfectly for this to work," says Tianlu Wang: "The thickness of the dielectric so there's no spark discharge between the electrodes, the thickness of the films, and a few other things."

Until now, Wang says, fish or jellyfish robots have typically used small electric motors that operate at voltages as low

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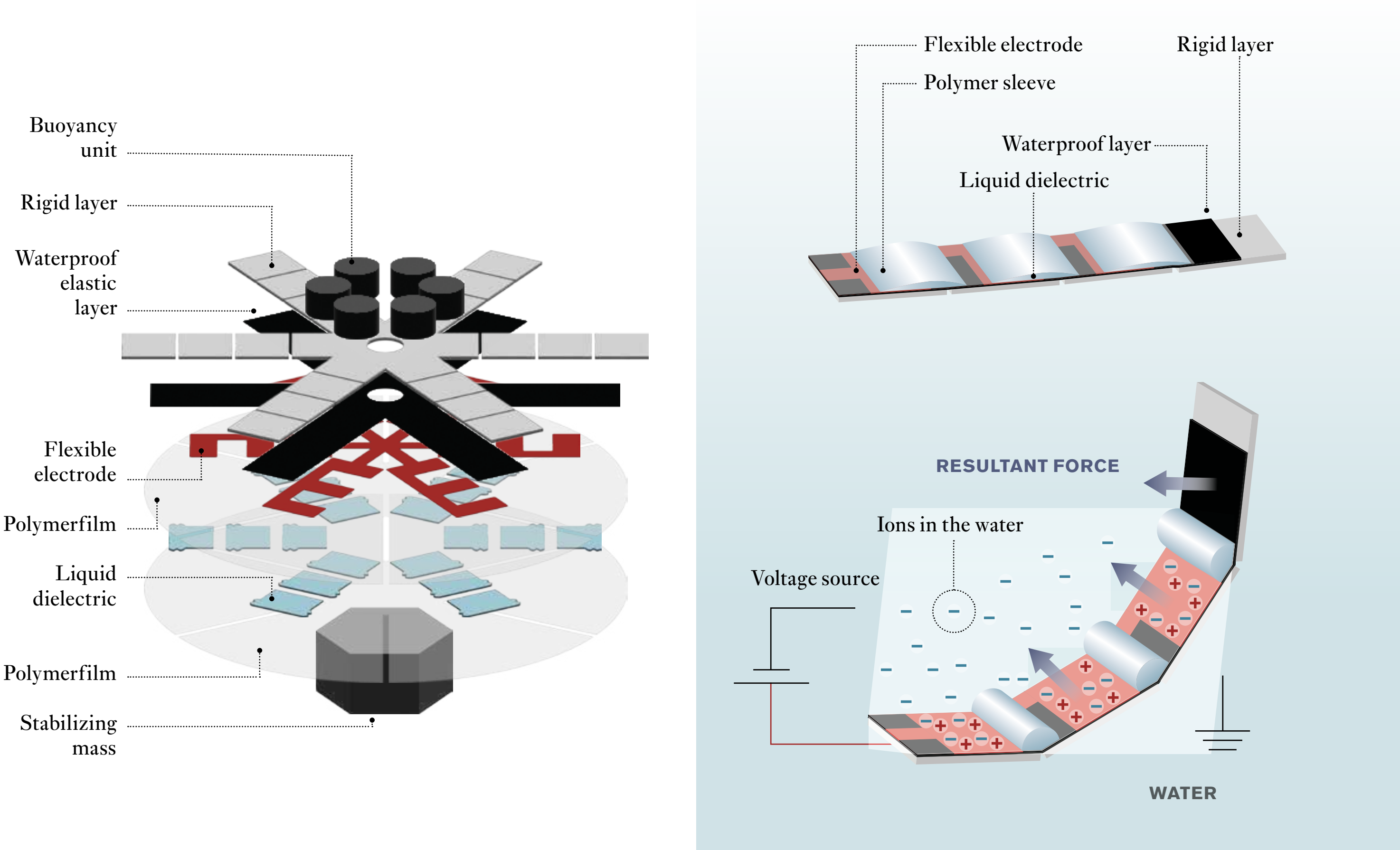


A moving sandwich: The jellyfish-bot is made of, among other things, waterproof film, flexible electrodes and a dielectric such as silicone oil. The combination of buoyancy unit and stabilizing weight keeps it upright in the water. Its arms bend when a voltage is applied to the dielectric (right). Ions in the water, but also the polar water molecules that attach to the arms, intensify the electric field and thus the contraction of the artificial muscles.

GRAPHICS: GCO ACCORDING TO WANG ET AL., SCI. ADV. 9, EADG0292 (2023)

as a few hundred volts. But these motors consume significantly more electricity. This jellyfish-bot, on the other hand, works with high voltage but only requires an electrostatic field to trigger movement. A small power output of around 100 milliwatts is sufficient for this – as much as a toy car. “Otherwise, there would also be far too great a risk of electrocution,” Wang says. Despite its low wattage, a jellyfish-bot accomplishes quite a bit. Since its arms can be controlled individually, it can grip objects with two arms while the other four provide propulsion. Moreover, the robot can fan out its arms and use them to fetch small objects. This could help not only with cleanup, but also with marine research. For example, in the future, marine biologists could use it to collect fish eggs or other samples.

For more demanding underwater applications, the researchers would still have to equip the jellyfish robots with their own energy supply – such as solar cells on the rowing arms – as well as microchips for control and signal processing. Wang: “The necessary technology is already available today at a low cost.” This would enable the swimming robots to work independently, i.e., without cables. While they will still probably be controlled remotely via radio for the foreseeable future, it is also conceivable that they will at some point act independently with the proper programming.

Soft robotics is gentle by its very nature

Aeronautical engineer Victoria Gerrlich of Bremen’s Marum Center for Marine Environmental Sciences also thinks the jellyfish-bot is promising, and not only for underwater research. She is currently developing a “soft robotic” gripper in a project at the German Aerospace Center. In the future, it will be used for scientific observations in space, where water is found under ice sheets – for example on Jupiter’s moon Europa, under whose ice mass geologists suspect there is liquid water. The gripper will one day deploy and retrieve an underwater vehicle equipped with sensitive sensors under the ice. “Soft robotics for use underwater is a totally new concept,” says Gerrlich. “I can only imagine the long road our colleagues in Stuttgart have traveled with their jellyfish-bot.” Many specialist articles have already been published on the subject of soft robotics for underwater applications. “Ultimately, it’s so new that you basically have to design, build, and test everything yourself.” For marine research, such grippers are essential –

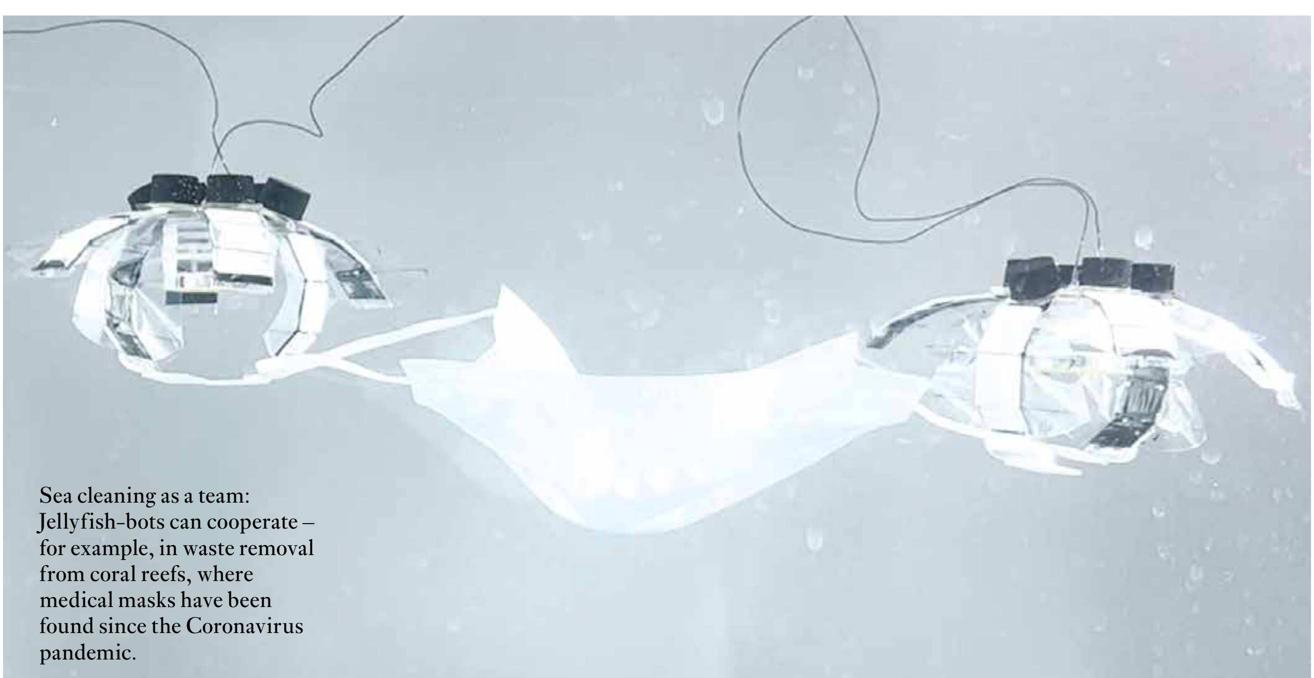
not only for picking up trash, but also for collecting samples of plants or animals. Gerrlich: "Until now, hard grippers have been used for this purpose. They are equipped with sensors to ensure that they grip gently. But soft robotics is gentle by its very nature and can do very little damage. I think it's exciting that the Stuttgart researchers are working in this area." However, it is important to use biodegradable materials for such robots in the future so that they do not pollute the sea themselves, should they ever fail or become lost. As it turns out, materials expert Hyeong-Joon Joo of the Max Planck Institute in Stuttgart is already working on this.

In other respects, the Stuttgart team is already a step ahead: Tianlu Wang is particularly proud that he and his electrical engineering colleagues have succeeded in making several remote-controlled jellyfish-bots swim together. "In fact, our jellyfish can even cooperate," he says. He opens some photos on his screen. The images show two jellyfish-bots picking up a face mask from the bottom of an aquarium and swimming away with it. The Stuttgart team came up with the idea for this experiment when they saw pictures of coral reefs in the media during the Coronavirus pandemic in which more and more face masks were collecting alongside the usual plastic waste. Tianlu Wang: "I think it's entirely possible to clean up sections of the ocean in the future with a squad of jellyfish-bots. Not everywhere, but in ecosystems that are particularly vulnerable."

According to a recent study in the journal Nature, an international team of researchers found plastic waste in 90 percent of all coral reefs studied. A particular problem is plastic net debris that can get caught in corals and break pieces of them off. Coral reefs covered with plastic bags and sheets are also less well supplied with light, nutrients, and oxygen. And according to a study by the Alfred Wegener Institute, they are between 20 and nearly 90 times more likely to be infected with pathogens. Plastic waste is also particularly harmful in mangrove forests, which are often found at the mouths of tropical rivers. For example, the trees in these ecosystems no longer grow properly when their roots, which grow in the water, are covered with plastic waste. However, it will probably be a few years before swarms of jellyfish-bots are able to clean up sensitive ecosystems. So, the next goal is to supply the jellyfish-bots with on-board power. Then perhaps the first squad will soon be able to take off for a major ocean cleanup. ←

GLOSSARY

HASEL
stands for *hydraulically amplified self-healing electrostatic actuators*. These are synthetic muscles that are moved by squeezing a fluid-filled bag through the force of attraction between two capacitor electrodes. Hasel muscles enable robots to make smooth movements, such as when engaging with humans or in sensitive environments.



Sea cleaning as a team: Jellyfish-bots can cooperate – for example, in waste removal from coral reefs, where medical masks have been found since the Coronavirus pandemic.

PHOTO: WANG ET AL., SCI. ADV. 9, EADG0292 (2023)