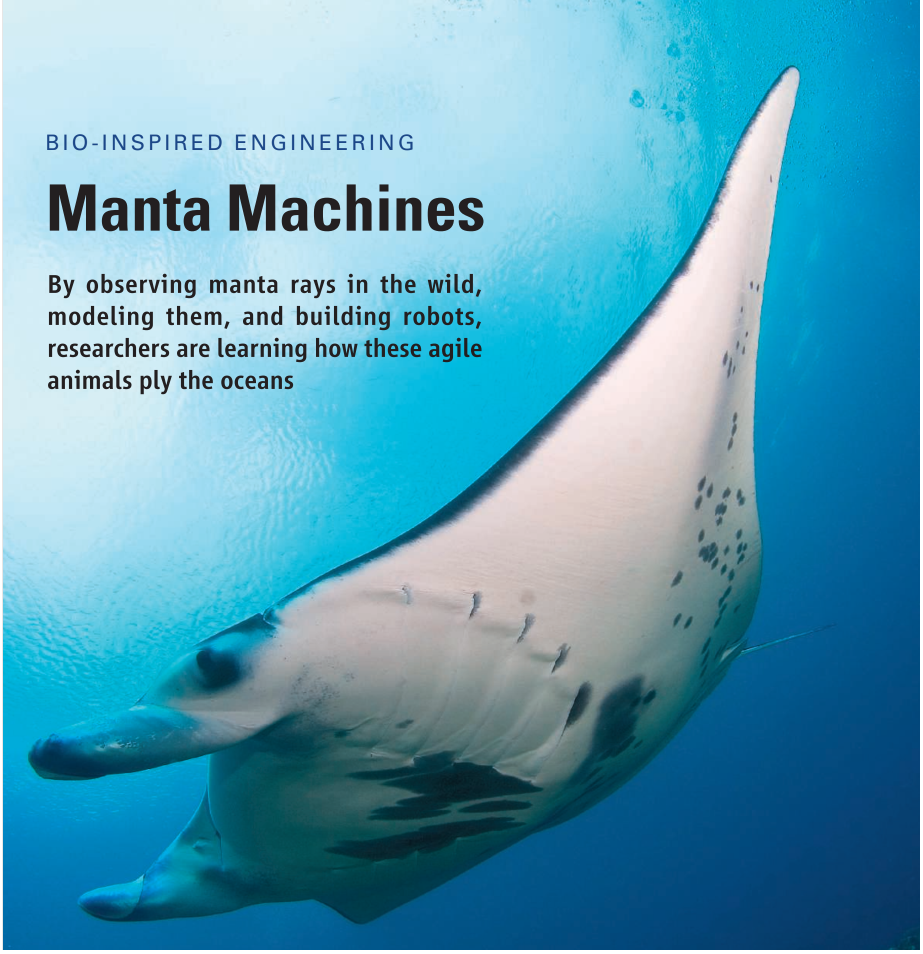
BIO-INSPIRED ENGINEERING

Manta Machines

By observing manta rays in the wild, modeling them, and building robots, researchers are learning how these agile animals ply the oceans



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Swimming like butterflies underwater, with mesmerizing ease and grace, manta rays are the envy of engineers seeking more efficient underwater vehicles. For the past 3 years, researchers at Princeton University and the University of Virginia (UVa) have been working to understand how these meters-wide fish are so light on their fins. Now, their students are putting the insights they have gained to the test—in a manta robot competition between the two collaborating universities.

On this April afternoon, Princeton mechanical engineering senior Mohammad Javed is scrambling to show how close his manta robot comes to emulating the animal's dexterity.

"Three minutes left," a judge calls out.

"I'm going to try one more time," Javed responds as he frantically lifts "A Bot Named Sue" out of the water to remove a weight from its back and to screw another weight onto its front. He needs to adjust the buoyancy enough that the robot can dive down a meter, swim under a bar, surface, and swim back over the bar.

Less than 3 weeks ago, his robot was still in pieces. The body of his first iteration leaked, ruining the electronics that moved the fins. By the time he got a replacement, he barely had time to test it.

Earlier in the day, UVa's contender, Manny, had dashed down the length of the pool at twice Sue's speed. But it was not as good at diving or turning as Javed's robot and never succeeded in the "under and over the bar" test. So this was Javed's chance to clinch victory. During his first try on this test, one of the servomotors driving the fins overheated and the robot shut down. This time around, the weights caused it to nose-dive to the bottom and flip onto its back so it couldn't come back up.

Javed puts the robot back into the water, and a diver positions it in front of the bar. It dives, but the weights still aren't quite right and the clock runs out.

There's no clear winner—the judges declared a tie—but the onlookers and the contestants are quite pleased. "For the first time out, [both teams] are doing pretty well," says judge Gilbert Lee, a materials scientist at the Carderock Division of the U.S. Naval Surface Warfare Center in West Bethesda, Maryland, where the competition is being held. "They were successful in achieving raylike propulsion," adds Robert Brizzolara, a program officer with the Office of Naval Research (ONR) in Arlington, Virginia.

Online
sciencemag.org
Podcast interview with author Elizabeth Pennisi.

That was the goal. Mantas are everything one could want in an autonomous underwater vehicle (AUV). "I've thought for a long time that the people who are interested in robotic mimicry were missing the boat in not looking at manta rays," says Adam Summers, a comparative biomechanist at Friday Harbor Laboratories in Washington state. Most fish swing their body from side to side, and "that's not very handy if you are trying to stuff [instruments] inside." The manta body is stiff. Mantas are also quiet, efficient swimmers—AUVs tend to be one or the other. The best AUVs have a turning radius of 0.7 body lengths; the manta needs just 0.27 its body length and maneuvers like a fighter plane. Based on the two robots' performance, "in terms of maneuverability, we're on the right track" in understanding how mantas achieve such grace, says Frank Fish, a functional morphologist at West Chester University in Pennsylvania who is working with UVa and Princeton on the manta project.

Understanding manta rays

The focus on manta rays traces back to a snorkeling trip Alexander Smits took in Australia about a decade ago. "They are such self-possessed, graceful animals," he says. "It was almost mystical," he recalls about his experience swimming among these 2-meter- to 5-meter-wide fish. "I decided I've got to know something about them."

An expert in experimental fluid mechanics at Princeton, Smits persuaded Hilary Bart-Smith, a postdoc at the time designing flexible aircraft wings, to consider instead developing shape-morphing fins for underwater locomotion, based on manta ray swimming. They couldn't get funding at first, so the research didn't get very far. But Bart-Smith took the project with her to UVa and got fellowships to work toward building an artificial structure that could recapitulate the highly maneuverable, seemingly effortless movements of manta rays.

Then 4 years ago, ONR issued Bart-Smith's dream request for proposals: a solicitation for "bio-inspired" sea vehicles. She called Smits and recruited him, Fish, and three other researchers to look at not just mantas but also other rays from biological, engineering, fluid dynamics, and modeling perspectives. In 2008, their proposal was awarded \$6.5 million over 5 years. "They've got a challenging problem to solve: to produce a flexible mantalike wing that could have its motion controlled accurately," says George Lauder, a biomechanist at Harvard University.

It fell on Fish, the biologist on the grant, to get the nitty-gritty details of the manta ray's swimming behavior. His first job was to catch the animals in action. For that he headed to

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Yap, an island in Micronesia where manta rays regularly visit the protected waters inside the island's reefs to be cleaned by tiny fish living there. Fish and his colleagues set up two video cameras in water 24 meters deep to capture manta movements in three dimensions. They came home with 36 hours of video.

Back in Pennsylvania, he and his team have been analyzing the videos through a painstaking process of digitizing key landmarks of the manta's body—the fin tip, eye, and so forth—frame by frame. "We want to define the motion for animals going at a variety of speeds as well as up and down maneuvers," he explains.

Already they have been able to figure out the details of how the winglike fins deform. Two waves are set in motion in the fins as they flap. One travels from front to back of the fin. A second ripple extends out from the base of the fin to the tip. "The motion is far more complicated than what we find from a dolphin or tuna," Fish explains.

To complement the video footage, Fish has used computed tomography (CT) scans to probe the internal structure of the fins of several ray species. UVa biomechanics expert Silvia Blemker used the scans to construct 3D renditions of the underlying cartilage, revealing large differences between the fin skeletons. "It's a very complicated structure, with many elements and many links," Bart-Smith says.

UVa computational hydrodynamicist Hossein Haj-Hariri has created mathematical models based on the underlying cartilage structures to learn how different skeletal configurations contribute to swimming performance. "To mimic [the fin] exactly is incredibly challenging," Bart-Smith says, so she wants to know how much they can simplify the robot's "skeleton" and still have it work well.

What Haj-Hariri does in a computer, Smits tries to do in a tank at Princeton. He and his colleagues have built manta ray fins of flexible plastic and examined water as it flows over them. They are testing how different fin shapes and movements affect thrust and efficiency in steady swimming.

From the videos, the researchers had observed that manta fins both flap up and down and undulate, sending a traveling wave from the front to the rear of the fin. "This undulatory part of the swimming is really the most important part of it," Smits says, based on his measurements. It is four times more important than flapping for propelling the fish forward.

Manta mimics. Mohammad Javed fixes his manta "bot" (*top*) in hopes of beating out UVa's competing robot (*below*).

CREDITS (TOP TO BOTTOM): E. PENNISI/*SCIENCE*; DEVIN PISNER

Making mantabots

Over beers one night, Haj-Hariri, Bart-Smith, and Smits decided to recruit undergraduates to the project for a competition in which the students build manta ray robots. "It's a good way to test out a variety of prototypes," Lauder says. "You learn a tremendous amount by trying to build something even before you think you know enough to try."

At UVa, Bart-Smith and Haj-Hariri organized a yearlong senior engineering class whose goal was to build a robot for the competition. The students used a cable-rod matrix—called a tensegrity structure—encased in a soft silicon material as a fin. Tensegrity structures are rigid rods held together by tensioning cables, which creates a stiff, lightweight structure. Pulling on the cables in different combinations bends the tensegrity rods into a curved shape that allows the fin to move up or down.

The CT scans gave the students a sense of the range of shapes and physical characteristics possible for ray swimming: They decided to follow nature's design fairly closely. Then they had to scale those parameters down from several meters to a robot that was 60 centimeters long from wingtip to wingtip. Whereas the real fish has muscles in the fin itself, the UVa team put their "muscles"—devices called actuators—inside the "body" to reduce the weight of what had to move up and down. The body itself was made with a 3D printer, but because the plastic used was porous, they had to coat it with epoxy.

They studied the videos to decide on their turning strategies. For fast turns, they held one fin steady and flapped the other vigorously; for slow ones, they flapped the inner fin more slowly than the one on the outer edge of the turn.

At Princeton, Smits and his team persuaded Javed to represent them in the competition as the university's sole contender. His robot looks less manta-ish than UVa's. Seen from above, the UVa manta ray fin is triangular, but Princeton's is much more lobular. Javed put a horizontal rudder in the back that moves up and down and helps pitch the manta for diving and surfacing.

His manta's body is a single piece of machined plastic sealed with a lid screwed down like a manhole cover. Instead of containing a tensegrity structure, each fin has four parallel steel cables the diameter of toothpicks that extend from the body core toward the tip. They are arranged with two on top and two on the bottom and connected in the body to a cylinder driven by a servomotor. Pulling on the top cables curves the fin upward; pulling on the bottom causes the fin to flap downward.

Each team had 1 hour to complete five tasks: the over-and-under bar move, diving to the bottom of the tank and resurfacing, making the tightest 360° turn possible, going the fastest for a specified distance, and demonstrating the robot's swimming prowess with a freestyle maneuver. Both teams excelled at flapping the fins, but both had issues with buoyancy and water leaking into the bodies. But that didn't faze Brizzolara. "In any number of technologies that I have been associated with, the first time they put something in the water there are always hiccups and bumps," he says. Just getting to this point of having robots to test was "a step forward in the science."

Bart-Smith hopes to hold another robot competition next year. One of her UVa colleagues has built his own manta ray robot, one that is supposedly waterproof. And a company in Germany has a version whose fins are based on fish tail mechanics. Manta "bots," Summers says, are "getting far enough along that people are learning something about how the animals work by looking at how the robots work."

–ELIZABETH PENNISI

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