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2020
CASE STUDY

Shedding Light on the Dark Ocean Depths

Learn how researchers from the Monterey Bay Aquarium Research Institute study gelatinous sea creatures using novel PIV methods and high-speed imaging.

You don't have to dive 10,000 leagues under the sea to encounter some of the world's strangest creatures. Sometimes, 4,000 meters is enough.

Joost Daniels is a senior research technician for the Monterey Bay Aquarium Research Institute (MBARI) Bioinspiration Lab, an oceanographic research group that develops new technologies to explore and better understand the mysteries of the deep sea. The lab uses many tools, from lasers to high-speed cameras, to study the biomechanics and fluid dynamics of midwater animals during feeding and swimming. This work includes lab investigations, or as MBARI calls it, "bringing the ocean to the lab," as well as deep-sea studies using remotely operated vehicles (ROV), or "taking the laboratory into the ocean."

It is the Bioinspiration Lab's hope that the results of these endeavors will lead to new developments in ocean instrumentation and bio-inspired engineering designs—some of which can help scientists combat the dangerous effects of climate change.

Image: 3D reconstruction footage of a Forskalia siphonophore, *imaged using the Phantom VEO 640.*

VISION RESEARCH

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MIDWATER MYSTERIES

Daniels' research applies to the midwater, which is the area between the ocean's sunlit upper layers and the deep sea's dark floor. Here, roughly 4,000 meters below the surface, the animals have adapted to thrive in a three-dimensional, fluid world without boundaries.

This habitat is home to some of Earth's largest ecosystems and animal communities, and for over 20 years MBARI has deployed ROVs equipped with high-resolution scientific cameras to explore these depths. The vehicles dive into Monterey Canyon, one of the deepest submarine canyons on the U.S. west coast, and collect in situ (at a specific location) data, including the identities of midwater species, as well as various water properties. This information is useful in providing a baseline for studying not just the animals, but seasonal cycling and climate change.

Parallel to this in situ work below the water, Daniels frequently conducts experiments in the lab using water and animal samples collected by the ROVs. "The midwater animals we study are strange," Daniels admits. "They're gooey, transparent and don't have a lot of dry weight." For example, one of the Bioinspiration Lab's areas of focus is tomopterid fluid interactions, with *Tomopteris* referring to a bioluminescent and transparent deep-sea worm. "This creature has evolved to swim efficiently and in a visually striking way," Daniels says. "We want to know how and why this animal evolved to move like that."

EXPANDING TRADITIONAL PIV METHODS WITH DeepPIV

Whether underwater or in the lab, Daniels and his fellow researchers use a range of tools and technologies to study the often-strange midwater world, including particle image velocimetry, or PIV *(read "Exploring Traditional PIV")*, and advanced imaging techniques. The team has also developed and frequently operates DeepPIV, an instrument originally created for studying and directly measuring the animals in situ using the ROVs. DeepPIV, which takes traditional particle motion analysis out of the lab and into the sea, uses a laser sheet and high-resolution camera to illuminate and record suspended particles moving in seawater. Using this technique, Daniels and team can create three-dimensional renderings of *Tomopteris* and other transparent sea creatures. The laser sheet penetrates cleanly through the animals, creating cross-sectional images of their gelatinous makeup. These resulting image stacks are then used to generate 3D reconstructions, which provide new and sometimes never-before-seen views of the animals' internal structures.

EXPLORING TRADITIONAL PIV

In addition to the novel DeepPIV approach, high-speed cameras enable MBARI researchers to measure particle movement using traditional PIV techniques, which introduce seeding particles into a flow. A popular imaging method for motion analysis, traditional PIV uses a laser sheet to create a two-dimensional plane. Seeding particles reflect the laser when they fall into the plane and are imaged using high-speed cameras in a single view or with stereo pairs. During post-processing, researchers can render a vector map of seed cloud movements from these image pairs and take velocity measurements based on grid divisions of fluid movement within the field of view.

In the lab, Daniels records these experiments using a Phantom VEO 640 high-speed camera, which enables him to scan a tank of water much more quickly compared to the standard high-resolution cameras deployed on the ROVs. "The high-speed cameras really make a difference," Daniels explains. "The 3D constructions, much like CT scans, rely on the animal moving as little as possible to avoid motion artifacts. The faster we can perform the scan, the better."

Because the laboratory is a controlled environment, Daniels is also able to gather information about midwater animals that would be impossible to distinguish in situ. For example, high-speed images of *Forskalia siphonophore* reveal elements of the animal's structure "lighting up" in a sequence as it moves through the water *(see Forskalia siphonophore images)*. "We wouldn't be able to obtain this visual information about the animal's movement using DeepPIV, which involves bringing a 10,000-pound ROV around such tiny animals," Daniels says.

While Daniels typically records these lab scans between 300 and 1,000 frames per second, the VEO 640 achieves 1,400 frames per second at full, 4-megapixel resolution. The proprietary CMOS sensor incorporates 10 micron pixels with high light sensitivity, a quality critical for biological imaging, making the camera an ideal tool with the resolving power required for subjects of this nature.

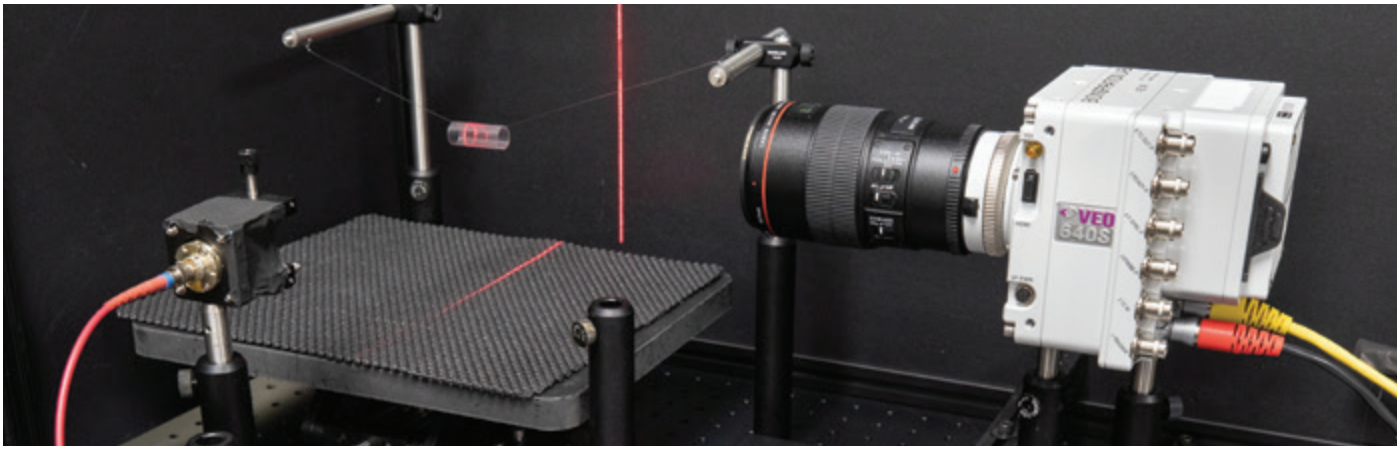


Image of the lab's 3D reconstruction setup with a test object (a plastic cylinder) in the laser. Also pictured is the Vision Research VEO 640 high-speed camera.

WHAT THIS WORK MEANS FOR OCEANOGRAPHIC RESEARCH

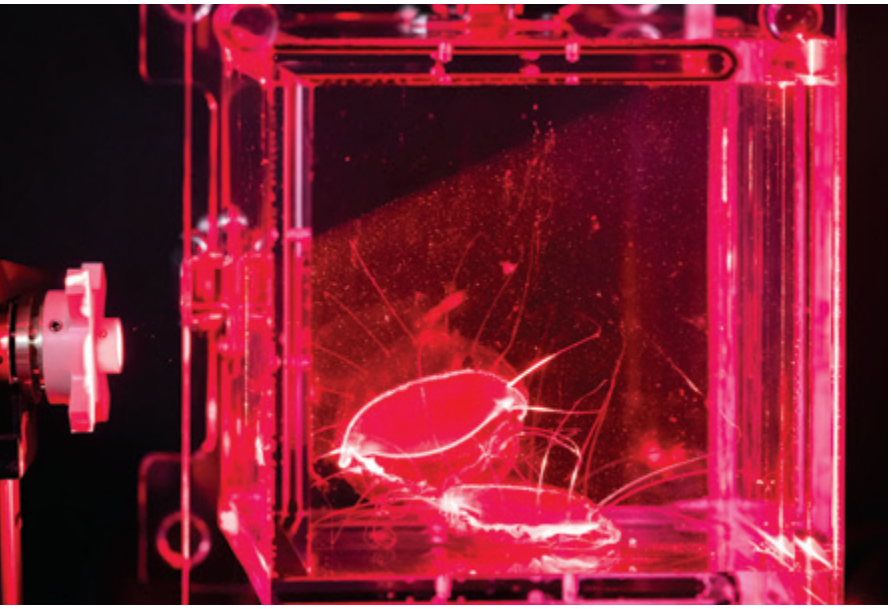
Because *Tomopteris* and other midwater organisms are mostly made of water, it has been a challenge for researchers like Daniels to visualize, draw or photograph the animals, as well as understand the animals' biomechanics and bio-fluid dynamics. "But thanks to the 3D reconstructions from DeepPIV, we now know what many of these animals look like and how they move and feed," Daniels says. "We can apply this data to what we know of other animals, streamlining new species discovery and taxonomy."

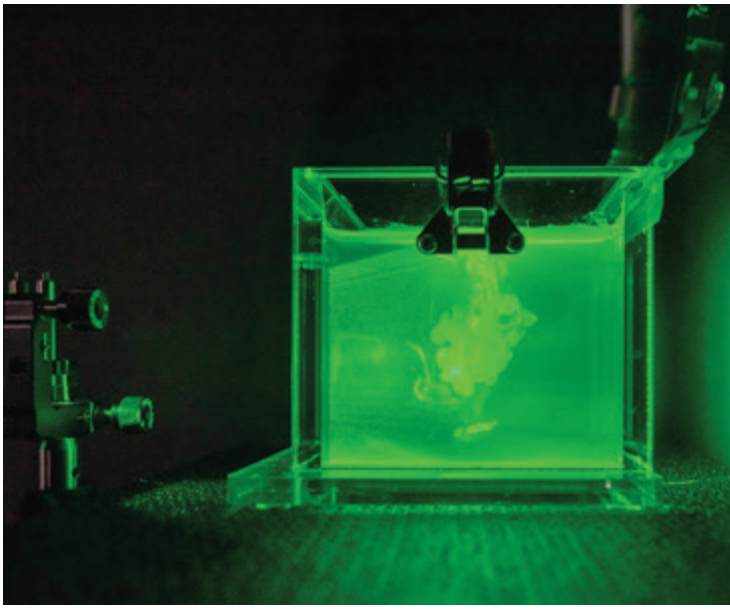
The Bioinspiration Lab's research also has implications for the development of bio-inspired technologies. For example, despite the tomopteris' unique body plan, "its motion is similar to the way krill moves," Daniels says. "This tells us the motion is an efficient way to swim through the water at small-size scales." Since both creatures have evolved to create a similar hydrodynamic effect, studying these biomechanics can inform the design of new, more efficient underwater technologies.

A DEEP DIVE INTO DeepPIV

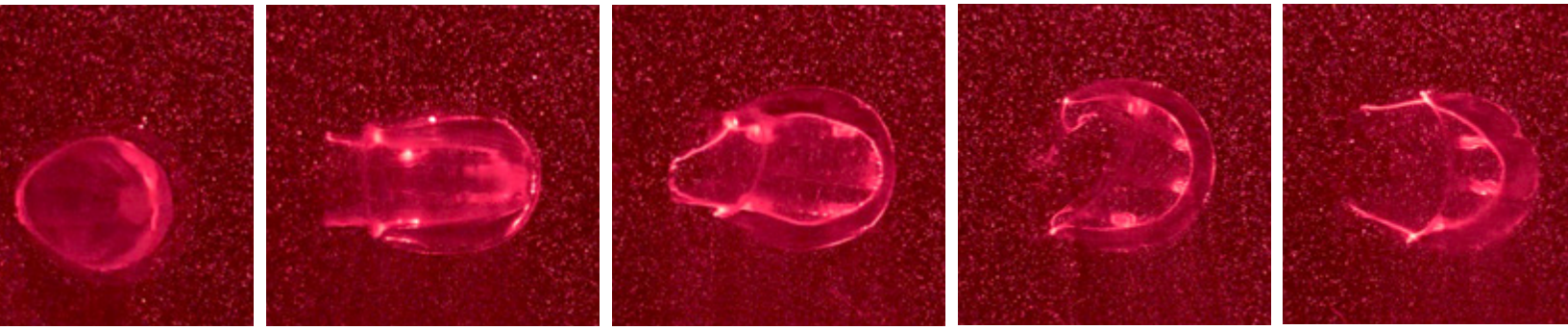
DeepPIV enables the MBARI researchers to deploy ROVs to depths where midwater organisms live, swim and feed. The instrument consists of a laser housing, which is deployed via a rigid arm that attaches to an ROV. The housing contains a continuous, 1-watt, 671-nanometer laser, as well as line-generating optics, that create a sheet of light 1-millimeter thick, creating an illuminated area as large as 20 x 20 centimeters. A high-resolution camera, equipped with a 10X optical zoom, captures the motion of suspended particles in the laser sheet at 60 frames per second, enabling the researchers to quantify the motion of the midwater fluid.

In the safe confines of the lab, the researchers swap out the standard cameras with Phantom VEO 640 high-speed cameras, which record scans of water tanks between 300 and 1,000 frames per second. Using high-speed cameras for this process creates accurate, detailed images for further motion analysis.





Left: Image of two Solmissus *jellyfish in the PIV / 3D reconstruction imaging setup. The laser is projected from the left, and light is scattered by the semi-transparent animals and particles in the water.* ***Right:*** *Imaging flow in a PIV laboratory setup using a green laser.*



PIV sequence of a swimming Colobonema *jellyfish, imaged using the Phantom VEO 640.*

OPENING NEW DOORS FOR CLIMATE CHANGE

In addition, the measurements of particle movement, as well as the three-dimensional reconstructions, have given the Bioinspiration Lab new insights into the interior flow patterns of midwater animals. In one unique case, this information has even gone a step further, opening up new, exciting doors in the study of climate change.

One of the lab's areas of focus is the ecology of giant larvaceans, which are transparent planktonic animals that live in the midwater. These animals, particularly their grazing habits, play a vital role in removing carbon from the atmosphere. Larvaceans build complex, food-filtering mucus structures—sometimes several feet in length—that contribute significantly to this "biological pump." These structures enable each larvacean to filter food and carbon particles in the water at an astonishing rate of 80 liters per hour. Once the larvacean abandons its structure after about 24 hours, the mucus sinks to the ocean floor, keeping the carbon trapped and out of the atmosphere.

MEASURING LARVACEAN FILTRATION RATES

The laser sheet used during DeepPIV can reveal the structures within a larvacean's mucus house, including the inlet and tail chamber size. By calculating the particle streak length within these two areas, the researchers were able to measure the larvaceans' filtration rates.

First, the researchers measured particle streak lengths through the entrance plane of the inner filter located near the posterior end of the tail. The number of particles measured per frame ranged from 1 to 10 over the course of the tail-beat cycle. They also recorded the maximum length of particle streaks for each frame, representing the centerline velocity within the entrance of the inner filter.

The researchers then found the average centerline velocity (U_{max}) through the tail-beat cycle by averaging the maximum velocity measured for each frame. Using equations for Poiseuille flow, they calculated the velocity profile within the tail chamber exit, where μ is the dynamic viscosity of seawater (1.08×10^{-3} Pa· s for seawater at 20°C) and r_0 is the maximum radius of the tail chamber:

$$u = -\frac{1}{4\mu}\frac{dp}{dr}(r_0^2 - r^2)$$

And, for a laminar flow:

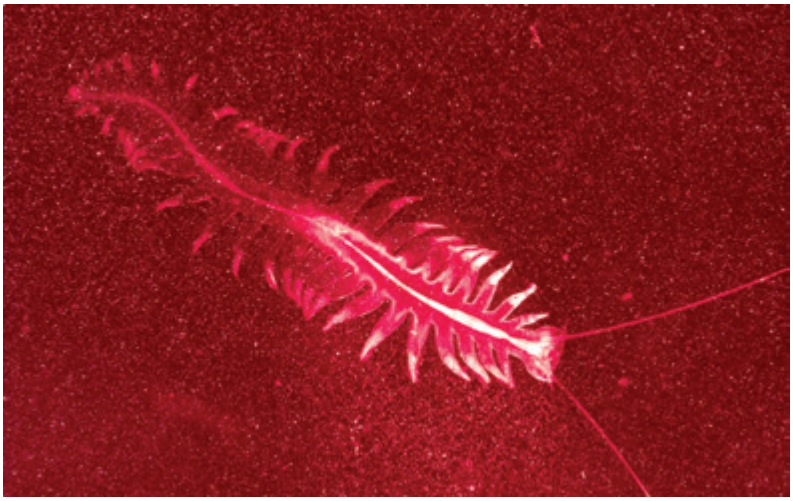
$$\frac{dp}{dr} = -4\mu\frac{U\max}{r^2}$$

Integrating the velocity profile (u) in the first equation across the tail chamber gave the researchers the average flow rate over the tail-beat cycle into the inner filter of the larvacean house. To determine the size of the larvacean and its mucus house, the researchers used sizing lasers and also placed an object of known size in the camera's field of view.

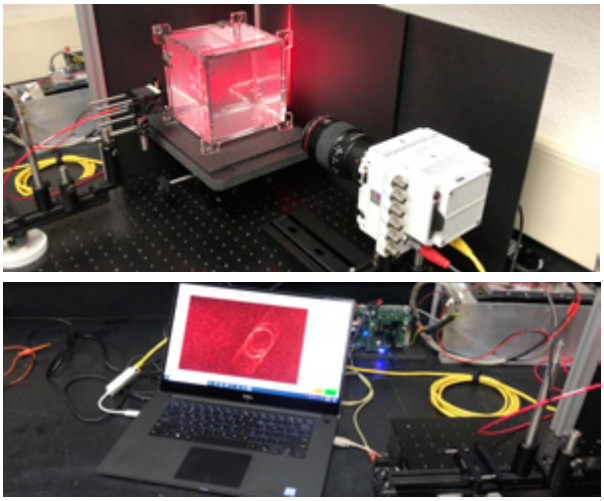
Using the measured dimensions of the inlet and tail chamber, the researchers found a cross-sectional area within the tail chamber and obtained the filtration rate by multiplying the cross-sectional area by the average flow rate into the inner filter.

Thanks to instruments like DeepPIV, the MBARI researchers can now create three-dimensional visualizations of these stunning mucus structures—also fondly nicknamed "snot palaces"—as well as see inside the larvaceans that make them. This information has enabled the lab to quantify the animals' filtration rates *(see "Measuring Larvacean Filtration Rates")* and even assess the long-term removal of carbon from the atmosphere.

To learn more about the work of MBARI, please visit: www.mbari.org. For more information about Vision Research high-speed technologies, please visit: www.phantomhighspeed.com.



*This frame-grab features a polychaete (*Tomopteris *sp.) swimming through particle-seeded water in a lab-based PIV setup. The animal was imaged using the Phantom VEO 640.*



The 3D reconstruction setup, scanning the test cylinder in water.

Preview of the Solmissus *3D model on Sketchfab.*

MORE INFORMATION

K. Katija, R. E. Sherlock, A. D. Sherman, B. H. Robison. New technology reveals the role of giant larvaceans in oceanic carbon cycling. Sci. Adv. 3, e1602374 (2017).

Katija, K., Troni, G., Daniels, J. et al. Revealing enigmatic mucus structures in the deep sea using DeepPIV. Nature 583, 78–82 (2020).

To learn more about Vision Research high-speed expertise and equipment, visit ***www.phantomhighspeed.com***

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