Touch at a distance: The development and fabrication of bio-inspired pressure sensor arrays for underwater detection and supermaneuverability

SMART — Singapore-MIT Alliance for Research and Technology

censam

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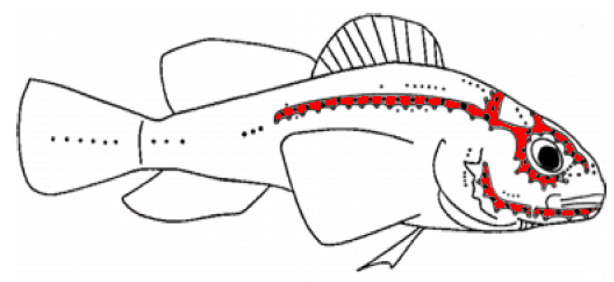
Goal: To design and fabricate pressure sensor arrays for a novel AUV sensory system inspired by the lateral line organ in fish

Relevance to Navy Technology and Education:

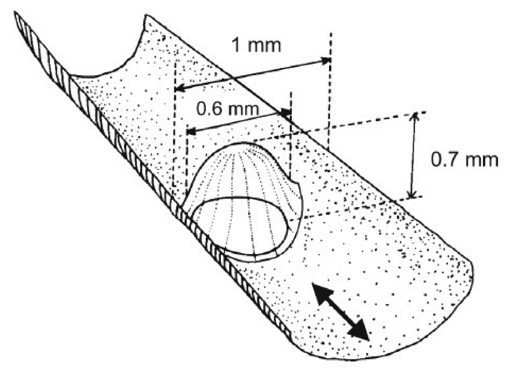
An important problem for navigation, maneuvering, and efficient propulsion is the detection and active manipulation of separated flow. Fish provide a unique solution through their lateral line. Developments in

- micro-pressure arrays
- methods to detect separation
- methods to actively control flow

hold the promise of revolutionizing the agility and performance of naval vehicles. As autonomous vehicles continue to develop a crucial role in U.S. Naval operations, it is necessary to remain on the cutting edge of vehicle design and optimizaton. The NEEC will help fulfill this crucial role by providing education on next generation technologies to sense and manipulate separated flow in order to maximize vehicle efficieny and performance.



Neuromast distribution in Lake Michigan mottled sculpin (adapted from Coombs, *Aut. Rob.*, 2001)



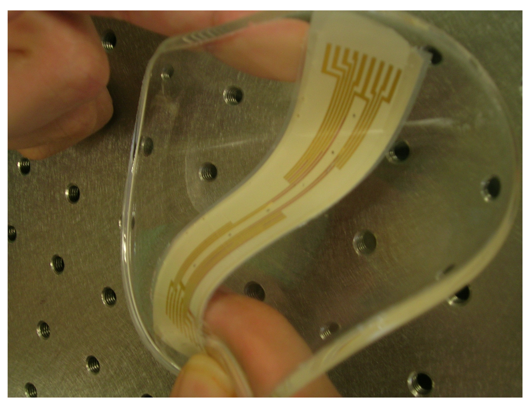
(Adapted from van Netten, *Biol. Cybern.*, 2006)

Motivation:

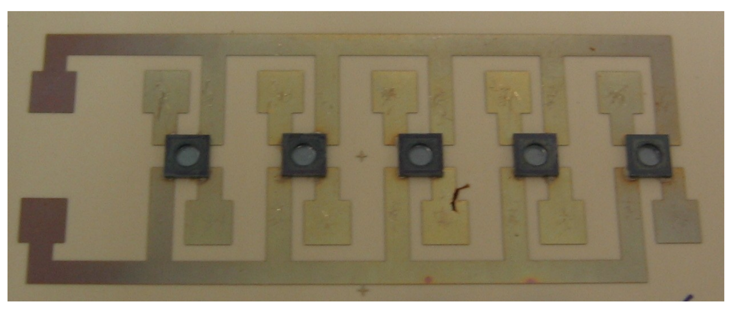
This research is inspired by the lateral line organ, found in all fish and responsible for many important capabilities and interesting behaviors. The lateral line in fish measures fluid flow velocity and pressure gradients on the surface of the fish body. Our interest is in emulating the fish canal system, which measures pressure gradients, and has been found to be responsible for a number of behaviors in fish that could also directly benefit AUVs.

To emulate the abilities of the lateral line and apply to AUVs, novel microelectromechanical systems (MEMS) sensor arrays have been designed and fabricated which take inspiration from the lateral line. While the canal system measures the pressure gradient between adjacent pores, these sensor arrays take advantage of the proven capabilities of MEMS technology to measure a gauge pressure with a common reference.

Flexible Sensor Design



Flexible sensors can adapt to variable body geometry

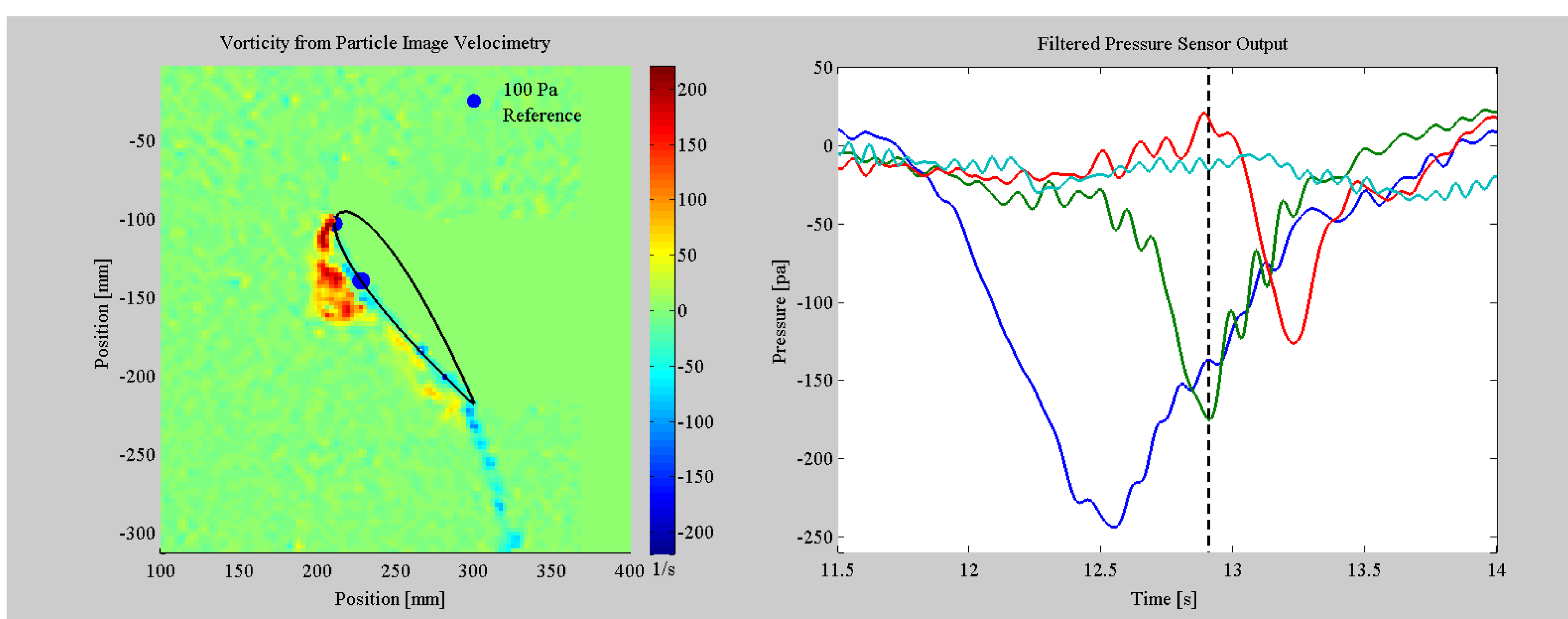


Small sensing dies allow dense arrays and greater resolution

The MEMs pressure sensors being developed by CENSAM aim to enable simple, affordable, and low power instrumentation of bodies of varied geometry. The key design feature of the piezo-resistive sensor design is the mounting of the silicone sensing dies on a flexible liquid crystal polymer (LCP) substrate. When encapsulated in silcone, the resulting sensor array is flexible and waterproof, enabling a wide range of mounting options and applications. Pressure sensors are attractive for naval appplications because they represent a completely passive method for identifying flow features, provide feedback to flow manipuation devices, and enable the detection and identification of objects.

Experimental Results

Vortices have a distinct low pressure signature that is readily discernible from the steady pressure gradient on a moving foil. Prior work at CENSAM has shown that vortex cores can be identified and tracked using an array of pressure sensors. By placing pressure sensors at four location along the foil in the chord-wise direction, a voretx shed from the leading edge was able to be identified as it was convected towards the trailing edge and away from the foil's surface. The magnitude of the pressure signal is seen to decrease as the distance from the pressure taps to the vortex core increased due to the foil's angle of attack. By using particle image velocimetry, the vorticity aroud the foil could be imaged simultaneously with the pressure measurements, allowing the position of the vortex to be verified.

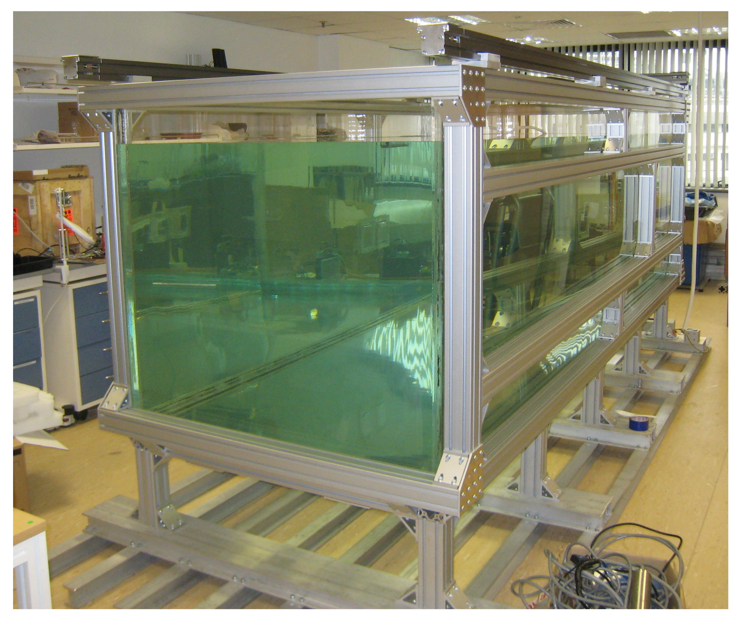


The location of a shed vortex can be verified by plotting the vorticity in the flow field around the foil found using PIV measurements. The location of the vortex in the above frame was found to be near the second pressure tap, and convecting from the top of the image to the bottom. The location of the vortex is in agreement with the sharp dip in the second pressure trace. The magnitude of the pressure at each pressure tap location is represented by the size of the blue dots.

The pressure sensor output during the PIV imaging period shows a distinct drop in pressure on each of the four pressure sensors as the shed vortex passes the corresponding pressure taps on the foil. The decrease in magnitude of the signal is consistent with the increasing distance between the shed vortex and succesive pressure taps. The black line represents the time shown using PIV measurements.

CENSAM Testing Tank

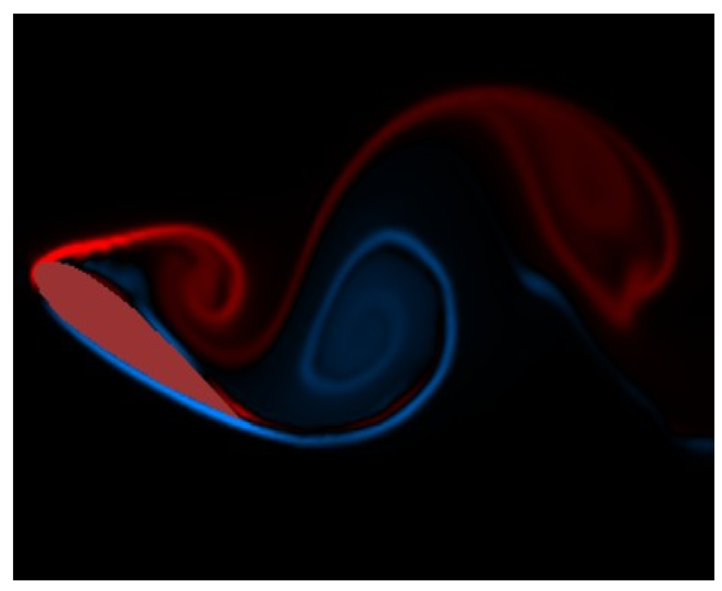
Many of the experiments done for testing and refining the estimation algorithms made use of the newly completed fluid test tank at CENSAM in Singapore. The tank was designed with these experiments in mind. The tank is large (1.2 m by 1.2 m by 3.6 m), with an x-y positioning system, and a carriage mounted motor allowing actuation in the z axis. The carriage allows accurate positioning over the entire horizontal plane, and is set up to accommodate conventional PIV as well as holographic 3D PIV.



The testing tank facility in CENSAM

Shed Vortex Detection

It is desired to detect and track vortices shed from the leading edge of hydrofoils using pressure sensing alone. Experiments were conducted at an angle of attack of 35 ° and velocities ranging from 0.1 to 0.45 m/s. In addition, trials were conducted using a combined sinusoidal pitch and heave motion at various Strouhal numbers and maximum pitch angles. In all cases combined pressure and force data were collected from the test body. Particle Image Velocimetry was used on select cases to validate findings.



Simulation by Dr. Gabriel Weymouth demonstrating the periodic shedding of vortices from a NACA 0018 foil at 35° angle of attack. Leading edge vortices are shown in red.

Experimental Apparatus

Experiments were conducted using a NACA 0018 foil with 15 cm chord and 60 cm span. The foil was cast in a female mold from rigid urethane with internal 0.318 cm (1/8") PVC tubing to transmit pressure from four taps at the foil's mid span. Four Honeywell 19mm series pressure sensors were mounted on top of the foil, and voltage measurements were collected with a labview interface. A six-axis force transducer from ATI was used to measure all forces and moments on the foil.

Above: NACA 0018 foil molded from solid urethane and instrumented with four commercial pressure sensors
Left: Pressure transmission tubes molded within foil

Acknowledgements

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