SEA GRANT FINAL REPORT
Energy Efficient AUV using a Lateral Line Sensor

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Summary

We have developed the capability for AUVs to emulate the function of the lateral line in fish, by designing pressure sensor arrays that can detect the flow patterns caused by external currents and fluid motion or by the motion of the AUV itself. Flexible and waterproof pressure sensor arrays were fabricated for use as a surface-mounted smart skin on marine vehicles. Two of the sensor arrays were based around the use of commercially available piezoresistive sensor dies, with innovative packaging schemes to allow for flexibility and underwater operation. The sensor arrays employed liquid crystal polymer (LCP) and flexible printed circuit board (PCB) substrates with metallic circuits and silicone encapsulation. The third sensor array employed a novel nanocomposite material set that allowed for the fabrication of a completely flexible sensor array. All three sensors were surface mounted on the curved hull of an autonomous kayak vehicle, and tested in both a pool and reservoir environment. Results demonstrated that all three sensors were operational while deployed on the autonomous vehicle, and provided an accurate means to monitor the vehicle dynamics. Additional tests on a stalling foil demonstrated clearly the capability of the sensors to detect and track separating flows, enabling control of vehicles for optimal maneuvering or motion within variable current. We are continuously improving the design of these sensors to incorporate further sensing capabilities to fully emulate the animal performance.

1. Introduction

Micro/Nano Electromechanical (MEMS/NEMS) pressure sensors are being developed in our laboratory at MIT and in Singapore for use on a wide array of surface and underwater vehicles. The development and fabrication of surface-mounted MEMS pressure and velocity sensor arrays is discussed, and the testing and calibration of the sensor arrays will be outlined. Also, the implementation and deployment of multiple MEMS sensor arrays on the hull of an autonomous surface vehicle will be presented along with results from field experiments.

1.1. Bioinspiration

In order to increase the situational awareness of marine vehicles operating in confined, cluttered, or hazardous environments we draw inspiration from the sensory capabilities of the lateral line organ found in fish and some other species. The outstanding ability of the Mexican blind cavefish (Astyanax fasciatus mexicanus) to navigate subterranean caves is particularly striking, because despite their atrophied eyes they can detect and avoid obstacles in cluttered caves, relying on their lateral line for navigation, feeding, and other essential behaviors.

The sensory units of the lateral line, the neuromasts, are spread across large portions of the surface of the fish body. Each neuromast sensor consists of haircells that are embedded into a cupula containing a soft gelatinous material. Each hair cell consists of a long kinocilium and an attached bundle of stereocilia, shorter and graded in height. The haircells are connected to the afferent fibers at the base and form the principal sensing element. There are two types, super_cial neuromast (SN) sensors with haircells as shown in Figure 1, that are freestanding on the surface of the skin and exposed to the flow, and canal neuromasts (CN) that are embedded inside lateral-line canals (Coombs et al. 2014, Webb 2014).

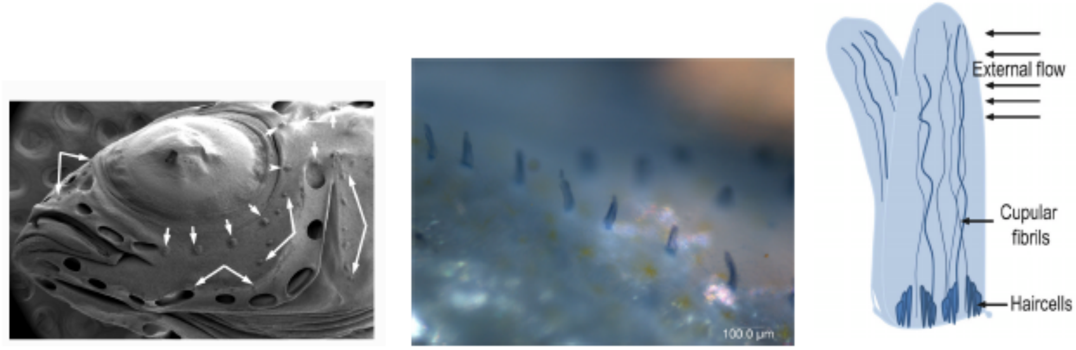

Figure 1*: (Left) Electron micrograph of juvenile cichlid fish with body length 11 mm, shows lateral line canals with large pores; presumptive CN under eye that will be enclosed in canals when older (short arrows); and SN (double arrows); opening between arrow heads on snout is the nostril (Webb 2014). (Center) Microscopic image of an array of cupulae of superficial neuromasts on the body of the fish, dyed with methylene blue (McConney et al. 2009). (Right) Schematic of a surface neuromast and cupula subject to flow (Kottapalli et al. 2013).*

1.2. Pressure sensing on hulls

For a vehicle operating in a marine environment, enhanced situational awareness has numerous benefits to control, navigation, and performance. Marine environments are highly dynamic, and vehicle motions are impacted by waves, wind, currents, and a wide variety of surface and submerged obstructions. In order to accurately control a marine vehicle, the vehicle dynamics must be well measured in real time. While these measurements are typically accomplished using inertial motion units (IMU), or digital compasses with built-in gyroscopes, hull mounted pressure sensor arrays offer an alternative method for measuring vehicle motions.

Experiments using a hydrofoil constructed with pressure taps on the foil surface indicated that the shape and location of stationary obstruction can be detected using pressure sensor feedback alone. While existing sensor technology greatly limited the distance at which an obstruction could be detected, the experiments demonstrated the potential for increasing environmental awareness by marine vehicles using a passive detection technique. Such a passive technique could be of great benefit for operation in noisy, cluttered environments, or where visual navigation is impaired due to a lack of light or poor water clarity. Passive methods for improving vehicle awareness are also attractive for missions where stealth and quiet operation is desirable. Also, the detection of strong vortex structures shed by a vehicle during maneuvering can be utilized to either increase vehicle maneuverability, or decrease the drag associated with rapid maneuvers. During maneuvering, streamlined bodies take on a large angle of attack relative to the mean flow, resulting in a cross sectional profie that is no longer streamlined, but similar to a bluff body. Because of this change in profile, helical vortices are shed from the vehicle, resulting in strong regions of low pressure near the body, as seen in figure 2.

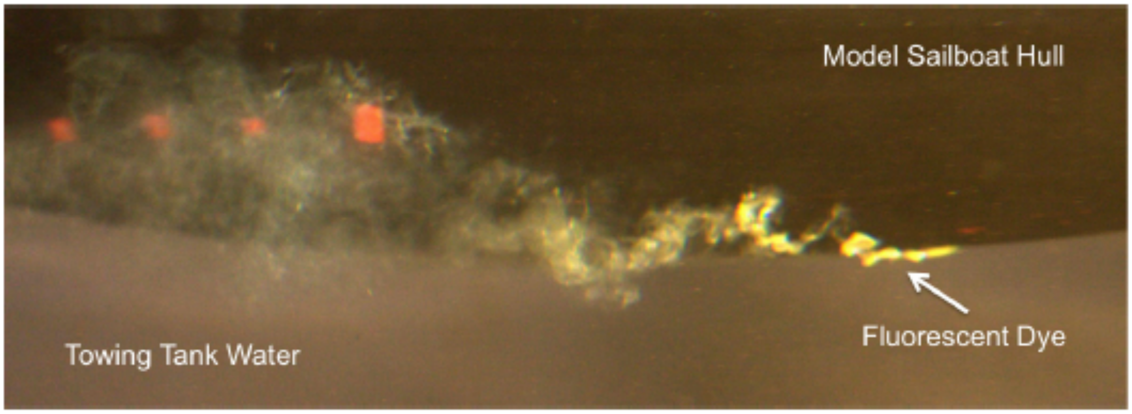

Figure 2: *When towed at an angle of attack, even well streamlined hull shapes, such as a model sailboat hull, present a bluff cross section to the incoming flow field. This drastic change in cross section results in the shedding of strong helical vortices from the hull's keel line. These helical vortices were visualized in the MIT Towing Tank by injecting fluorescent dye into the flow field at the keel line, near the bow of a sailboat hull. The dye could be clearly seen curling into a helical vortex that grew in diameter towards the stern of the model, and began to break apart due to the effects of viscosity.*

The presence of helical vortices, and their subsequent low pressure vehicle conducting a “lawnmower" search pattern, the additional drag at each maneuver can add up quickly, resulting in a reduced mission length. For an autonomous vehicle, battery life and mission endurance are the driving factors for cost, and the amount of usable data collected. If vehicle drag can be reduced through the use of active sensing and control through maneuvers, the benefit to ocean data collection would be significant.

1.3. MEMS pressure sensor array requirements

While previous experimental works within the MEMS pressure sensor group used commercial off the shelf (COTF) pressure sensors, these sensors do not meet all of the requirements of the MEMS pressure sensor arrays currently under development.

Of primary importance in the development of the MEMS pressure sensor arrays was to create a flexible and waterproof sensor array that could be surface mounted to a curved body, such as the hull of an underwater or surface vehicle. Additionally, it was desired to fabricate arrays of sensors that will ultimately mimic full body-length coverage of the fish lateral line.

The experiments conducted by Fernandez (2011), Dusek (2011), and Maertens (2011), utilized Honeywell 19 mm series pressure sensors for measuring surface pressure. The Honeywell sensors were found to have excellent robustness and sensitivity, but their large size (30mm height, 19mm diameter), and lack of waterproofing made surface mounting the sensors impossible. Instead, the sensors required mounting inside a waterproof housing, or mounting above the water surface, with pressure transmission tubes needed to transmit signals from the body surface to the sensors. In both cases, the size and water sensitivity of the sensors placed limitations on both the number of sensors that could be mounted on a body, and the size and shape of the experimental setup. Based on experience gained from these previous experimental studies, particular emphasis was placed on optimizing the flexibility and waterproofing of the MEMS pressure sensor arrays. Ultimately, it is desired to produce sensor arrays with sufficient flexibility, waterproofing, and robustness to allow for surface mounting on a wide variety of surfaces without the need for altering the sensing body in any permanent way. To achieve this goal, innovative, flexible, material sets were chosen for the fabrication of the MEMS sensor arrays.

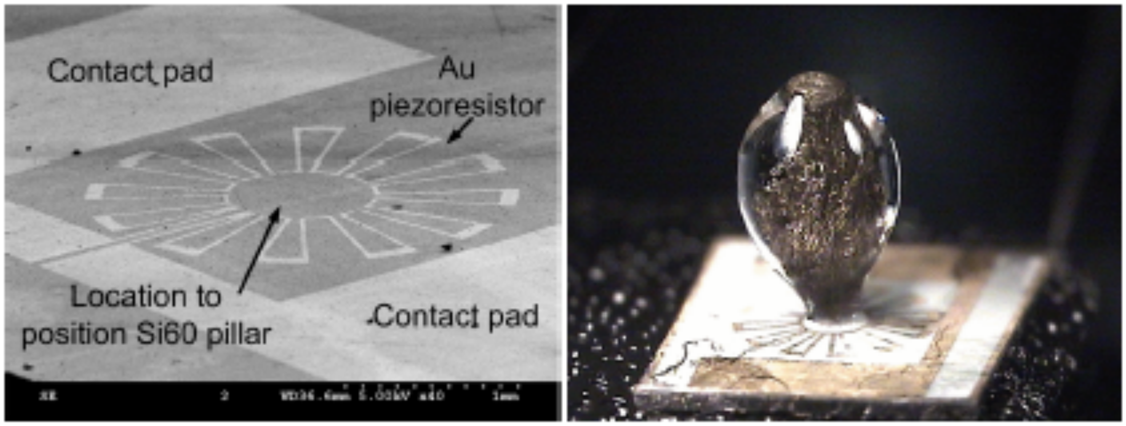

Figure 3: *Left: Image of an LCP membrane (diameter 2 mm) pressure sensor (Kottapalli et al. 2012a). Right: Piezoresistive sensor with cupula and encapsulated nanofibers (Kottapalli et al. 2013).*

2. Experimental pressure sensor arrays

Several sensor technologies are currently under development at MIT and in Singapore. Experimental sensor types are being tested both in the CENSAM testing tank, and on an autonomous surface vehicle (ASV) at the Pandan Reservoir in Singapore. Two of the sensor arrays were developed around a silicon pizeoresistive sensor die. The third sensor array was developed using an innovative conductive polymer material set.

2.1. Silicon Piezoresistive Sensors

For the two pressure sensor arrays developed at the Nanyang Technological University (NTU) in Singapore, commercially available pressure sensor dies were implemented using two different packaging schemes to create flexible and waterproof sensor arrays. Piezoresistive-based absolute silicon micro-machined pressure sensor dies (Model MS7201-A2 from Measurement Specialties Inc.) were chosen as suitable for deployment in harsh environments due to the construction of the pressure port from glass and silicon that is stable in most chemicals. Applied pressure was converted into electrical signal by the implanted piezoresistors in the silicon membrane, with packaging needed to provide the sensor die power and transport the output signal off the array. Other features included 0 to 100 kPa range, output span of 110mV at 5V supply voltage, temperature range from -40_ to 150_ C, small die size (1.35 x 1.79 mm$_2$), affordability, and high reliability.

2.2. Conductive Polymer Pressure Sensor

The third pressure sensor array deployed on the ASV was developed at MIT, and fabricated entirely from a polymer. Unlike the silicon piezoresistive pressure sensors that employed rigid dies on a backing, the polymer-based sensor was completely flexible. The active part of each sensor cell in the array was a strain-concentrating diaphragm molded from polydimethylsiloxane (PDMS), on which a piezoresistive strain gauge was patterned. A pressure difference across the diaphragm caused it to detect, and this detection was transduced by the strain gauge. PDMS was chosen as the sensor material, because its favorable chemical resistance and waterproofing characteristics are desirable for long term underwater usage. Additionally, its flexibility allows the sensor array to be compatible with the streamlined bodies of underwater vehicles, making it amenable to wide-area fabrication and deployment. The strain gauge was made of PDMS doped with carbon black. This composite was chosen because it is inexpensive, compatible with the main body of the sensor array, highly piezoresistive, and because it provides for repeatable operation.

To demonstrate the capabilities of the polymer-based pressure sensor array, one array was mounted on the hull of a kayak, and its pressure signals were recorded during kayak maneuvers in the Pandan Reservoir. For reference, the kayak hull was also instrumented with commercial pressure sensors at nearby locations.

2. Autonomous surface vehicle

To test the experimental pressure sensors under realistic conditions, an autonomous surface vehicle, operated with radio control, was employed. Based on a Pungo 100 rotomoulded kayak from Wilderness Systems, the vehicle provided a platform capable of carrying multiple experimental pressure sensor arrays, along with a suite of commercial pressure sensors and vehicle navigation instrumentation.

The kayak was equipped with two onboard computers within a custom waterproof electronics box. One computer was responsible for the control of the kayak's onboard sensors, which include a digital compass, GPS, IMU, and DVL. This computer ran Ubuntu Linux, and was loaded with MOOS-IvP software which both managed the data collection and saving, and could provide for autonomous operation if desired. The second onboard computer ran a Windows operating system, allowing for the use of National Instruments Labview software to be employed for collecting data from the commercial pressure sensor suite and the experimental pressure sensors. Labview provided an easy to use interface for collecting data from a large number of sensors, while also allowing visual inspection of the signals in real-time, enabling the operation of each sensor to be verified before deployment.

3. Field experimental results

The first series of experiments were conducted in a pool at the National University of Singapore (NUS), allowing for simple and controlled vehicle motions without the influence of waves or the vehicle's thruster. The second series of experiments were conducted at Singapore's Pandan Resevoir, and allowed for the sensor arrays to be tested in “real world" operating conditions.

4.1. Pool Experiments

Before taking the kayak vehicle to Singapore's Pandan Reservoir, experiments were conducted in one of the swimming pools at NUS to ensure the operation of the pressure sensors, as well as remote data collection from the vehicle. Because the pool at NUS was limited in size, experiments were restricted to simple vehicle motions that did not use the vehicle's propulsor. Unfortunately, the conductive polymer based sensors were not working during the initial pool tests due to an electrical problem that was remedied before conducting experiments at the reservoir. The two silicon piezoresistive sensors were found to be working, however, and responded well to various vehicle motions.

4.1.1. Roll Test

A roll response test was performed by forcing an oscillatory roll motion by hand in the pool. Because the silicon piezoresistive sensors were mounted on opposite sides of the vehicle, the signals from the two sensors 180_ were out of phase, as seen in Figure 4.

4.2. Pandan Reservoir Experiments

Experiments were conducted at Singapore's Pandan, which is located in the southwest portion of Singapore, is a drinking water reservoir managed by the Singapore Public Utilities Board, and is located near the Singapore-MIT Alliance for Research and Technology (SMART) center at NUS.

Unlike the experiments in the NUS pool, Pandan Reservoir provided sufficient space to conduct self-propelled experiments using the kayak's propulsor under radio control. A variety of experiments were conducted over the two-day testing period, including circles of various diameters, periodic turning motions in forward and reverse, approaches to docks and obstructions, and attempts to detect boat wakes.

For the experiments at Pandan, the electrical connection problems to the conductive polymer sensors had been resolved, enabling all of the sensors on the kayak to be used simultaneously. To ensure the conductive polymer sensors were operating as expected, the roll and pitch experiments without the thruster were repeated at the reservoir. It was found that for both the roll and pitch experiments, all three sensor types (commercial, conductive polymer, and silicon piezoresistive), worked as expected, as seen in Figure 4.

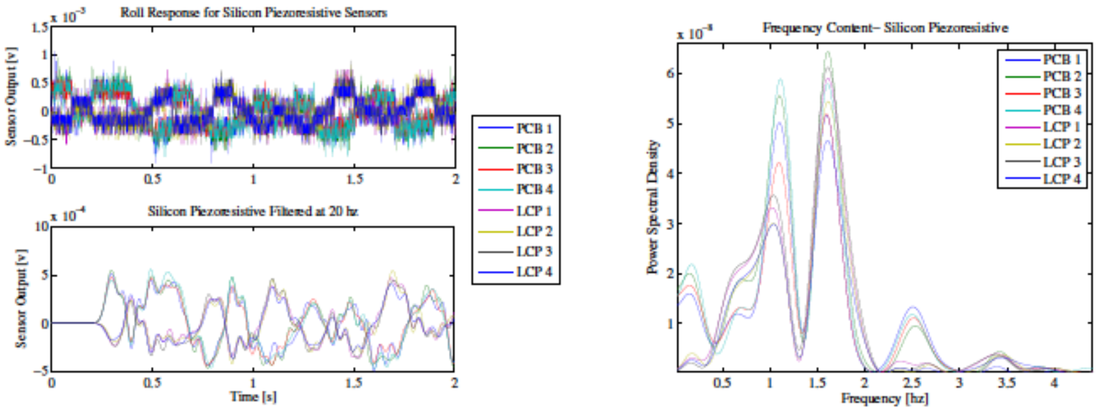

Figure 4: *Roll test on the kayak in the NUS pool. The two silicon piezoresistive sensors reacted as expected, with periodic signals 180 deg. out of phase. Right: Power spectrum for the silicon piezoresistive sensors during the pool roll experiment. Strong frequency components are observed at 1 and 1.75 Hz.*

4. Tests on Separating Flow

Tests were conducted on a foil at large angle of attack to demonstrate that the forming vortices can be detected with pressure sensor arrays. This is a major step toward developing optimal energy control systems for vehicles, avoiding the formation of separation wakes during maneuvering or when in cross-currents.

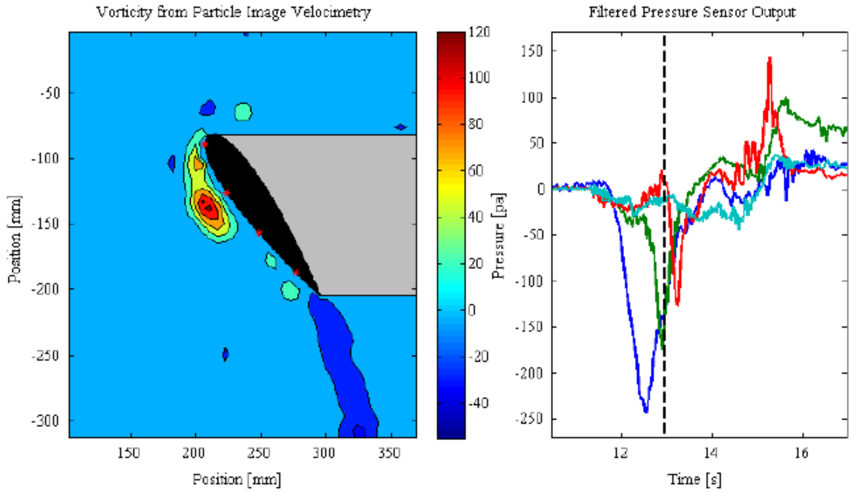

Figure 5: *Vortex detection on a stalling foil at an angle of attack of 35 deg., translating at 0.3 m/s, equipped with four pressure sensors (red dots on foil). Left: vorticity field obtained via PIV; a shed LEV is clearly visible adjacent to the second sensor. Right: time trace of pressure at the sensors, starting from the leading edge: 1 (blue); 2 (green); 3 (red); 4 (green). Vertical dotted line is at time corresponding to the frame at left.*

As shown in Figure 5, the highly characteristic deep-U pressure signature of a vortex, forming from the stalling foil leading edge, is tracked by all four sensors on the surface of the foil. Simultaneous PIV showed that the pressure measurements predict the development and evolution of the cortices with high accuracy.

5. Seal Whisker-Like Sensing

In addition to lateral line-inspired sensors, we have developed a novel sensing capability based on the vibrissae, or whiskers, of the harbor seal. Our work is inspired by harbor seals (Phoca vitulian) which often live in dark and turbid waters, where their mystacial vibrissae or whiskers play a significant role in orientation and in analyzing water movements (Hanke et al, 2010). Specifically, harbor seals exhibit a remarkable ability to detect and track prey using their whiskers (*vibrissae*) as flow sensors, by keeping them primarily perpendicular to the swimming direction. They do so by active touch and by sensing water movements caused by prey fish or other seals. Experiments in (Dehnhardt & Kaminski, 1995) suggest that harbor seals can use their whiskers as efficiently for active touch as monkeys use their hands! They can follow the path of water disturbances over distances that by far surpass the range of hearing or vision. Understanding the basic mechanisms of how vibrissae respond to the stimulus of the wake structures is crucial to the development of a bio-mimetic sensor capable of emulating the seal performance for underwater vehicle navigation. Such a sensor can be used to track an upstream target and identify obstacles in a cluttered or turbid environment. Because the fluid mechanics of *vibrissae* sensing is almost totally unknown, it is important to first characterize the vortex wake behind a whisker model, and the resulting vibrations of the flexible vibrissae is a crucial first step. In addition, it is interesting to investigate how seals cope with the flow resistance on their *vibrissae and* quantify it under different ocean conditions.

The use of seal whiskers as tactile sensing system has been previously investigated in (Mills & Renouf, 1986; Renouf, 1979; Dykes, 1975; Dehnhardt et al, 1998). Specifically, the seal whisker's function in prey detection was first documented experimentally by Dehnhardt et al, 1998; in these experiments, the seals were well isolated from all other sensory cues and used their whiskers to track the vibrations of a sphere underwater. The results indicated that the seal could detect very small perturbations in the flow.

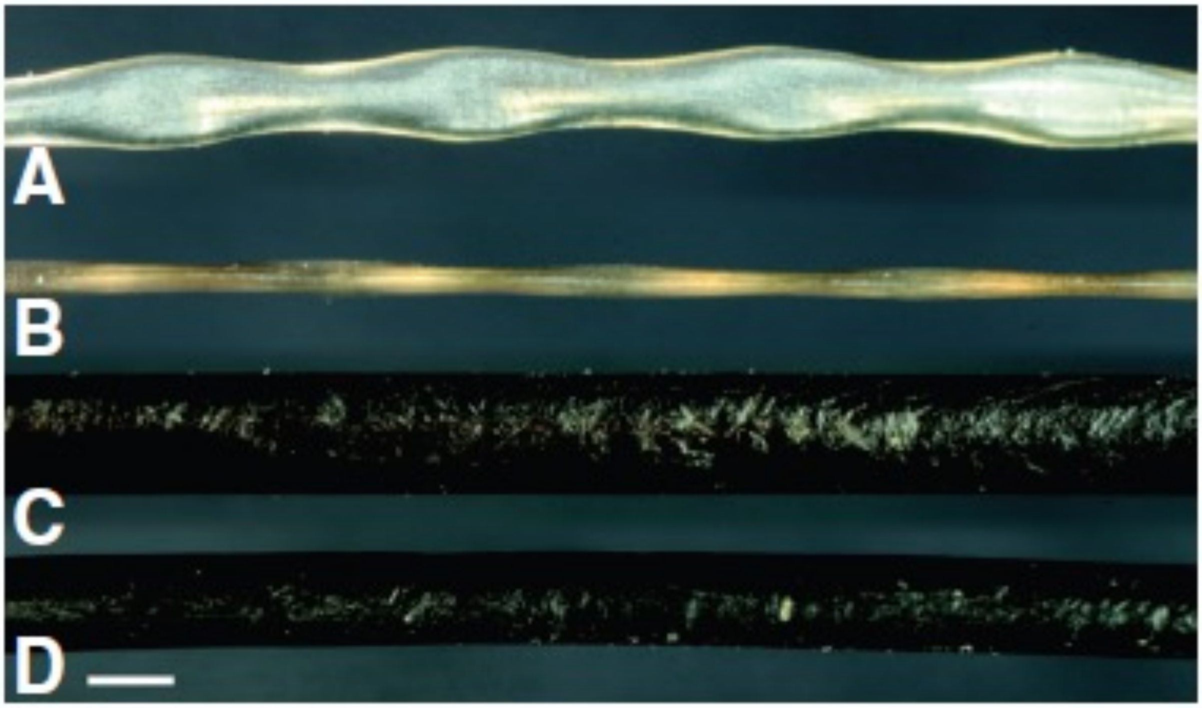

Figure 6: Structure of harbor seal (Phoca vitulian) and Clifornia sea lion (Zalophus californianus) vibrissae. (A,B) Harbor sea vibrissa in dorsal (A) and frontal view (B). The vibrissa is flattened in the dorso-ventral direction and possesses an undulated structure. (C,D) Sea lion vibrissa in frontal (C) and dorsal view (D). The vibrissa is slightly flattened and does not possess an undulated structure. (scale bar: 1 mm; adopted from Hanke et al, 2010).

The geometry of the *vibrissae* is intriguing, consisting of an elliptical cross-section with the ratio of the major to minor axis varying along the axis with a period of 1 to 3 mm, giving the flattened hair an undulated surface structure, see Fig. 2(A, B). This peculiar geometry is different from the vibrissae of eared seals such as the sdea lions, see Fig. 2(C, D). Recently, Hanke et al, (2010), using piezoelectric forced transducers and micro-stereo-PIV concluded that this special undulatory geometry of harbor seal whiskers may be used to suppress vortex induced vibrations (VIV). This is a surprising result, because the vibratory frequency of VIV can be used to detect the flow velocity. Our alternative explanation is that the VIV properties are *anisotropic*, hence allowing the seals to detect side components of the flow in preference to in-line components.

A basic research effort has produced a wealth of new information, which was used to develop effective sensing devices.

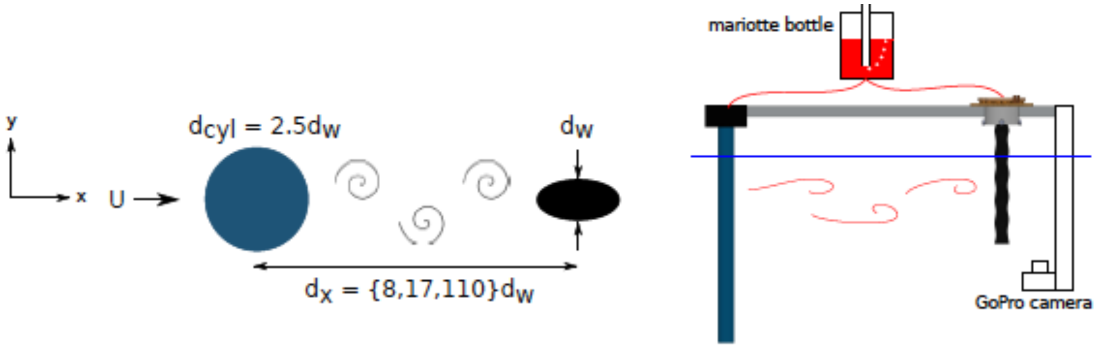

Figure 7: Model of the whisker (black) freely vibrating behind a circular cylinder (blue) demonstrated excellent detection of velocity and frequency of the Karman street. This is the first time that the whisker was shown to capture the frequency content of an oncoming wake, hence uncovering the novel mechanism through which seals are able to track prey underwater.

As shown in Figure 7, the whisker was tested behind a cylinder that sheds a Karman street and the flow was visualized using ink. We were able to show that the whisker always locks at the frequency of the cylinder wake hence explaining the outstanding performance of live seals in detecting prey up to 30 s after it has passed near them.

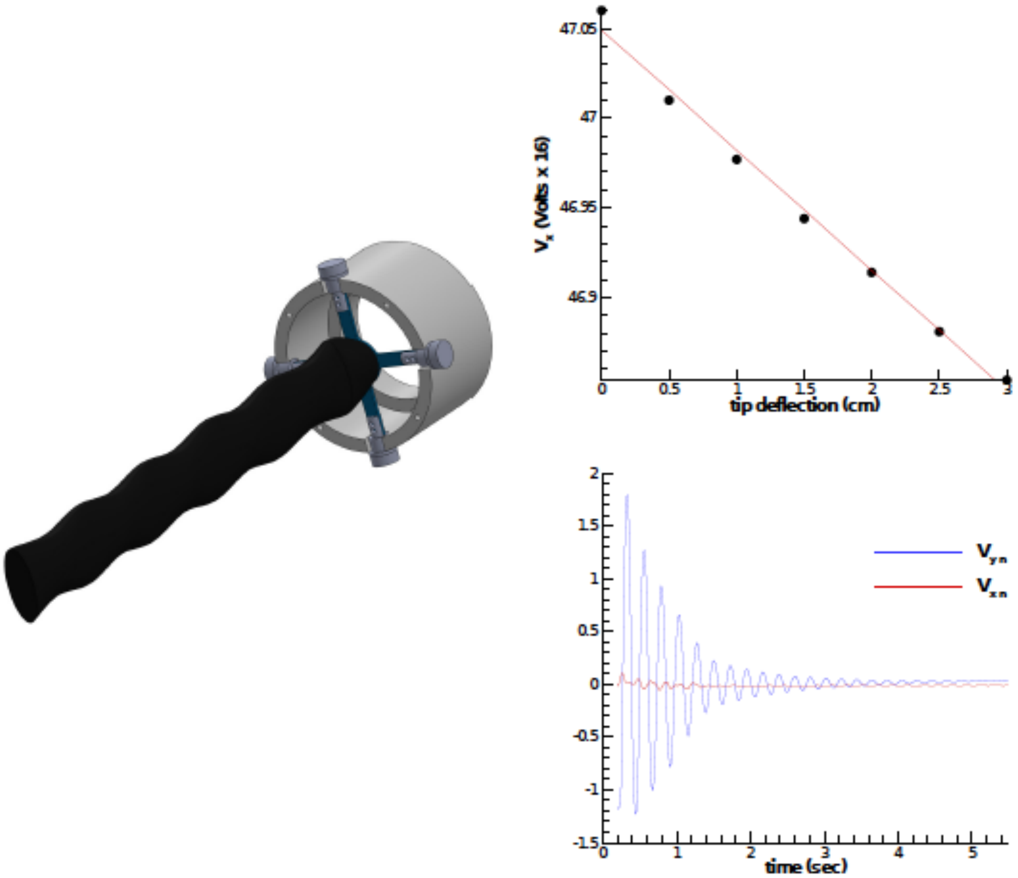

Figure 8: Whisker sensor mounted flexibly on force transducers. Calibration shows excellent linearity and provides for distinct natural frequency.

The sensor is shown in Figure 8 while Figure 9 provides the performance of the sensor. As seen, when the whisker sensor is placed behind a circular cylinder with 2.5 times the diameter, it oscillates with large-amplitude oscillation. This is in sharp contrast with the case of the same whisker in open water, where it moves very little. Hence the whisker can immediately sense the presence of a wake with very high precision, because of the very large signal to noise ratio. Equally important is its frequency locking capability as seen in Figure 9: The whisker ceases to vibrate at its own natural frequency and locks, instead, to the frequency of the Karman street formed by the upstream cylinder. This provides a unique detection capability since the Karman street frequency identifies the size and shape of the cylinder. Such results were repeatable up to large distances from the upstream cylinder (experimental testing up to 120 diameters apart), hence explaining how harbor seals can detect prey from relatively large distances and track with high accuracy their wakes, even 30 s after the prey has passed.

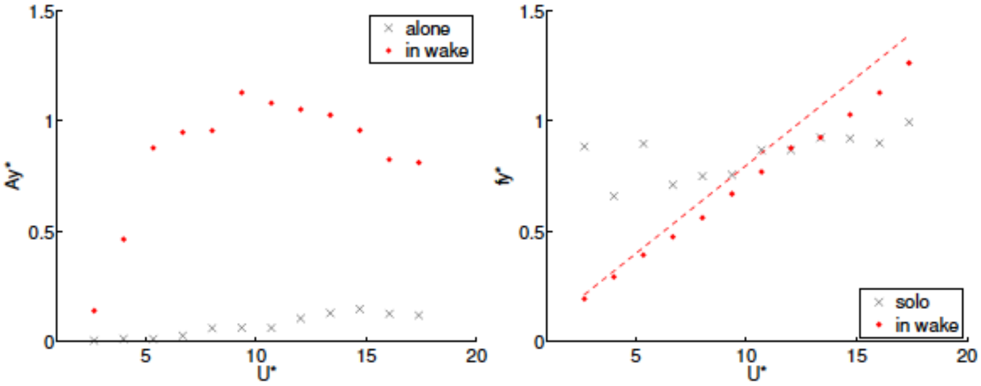

Figure 9: Response of the whisker sensor in the wake (red) versus in open water (dark). Large amplitude response within the wake provides high signal to noise ratio, while the excellent frequency-locking capability (right) provides unique feature identification capabilities.

Our work has produced further details on the mechanisms of flow detection that will be used for the construction of even more effective whisker-based sensors. Figure 10 shows some of the scaled up sensors produced on the basis of the seal whisker experiments.

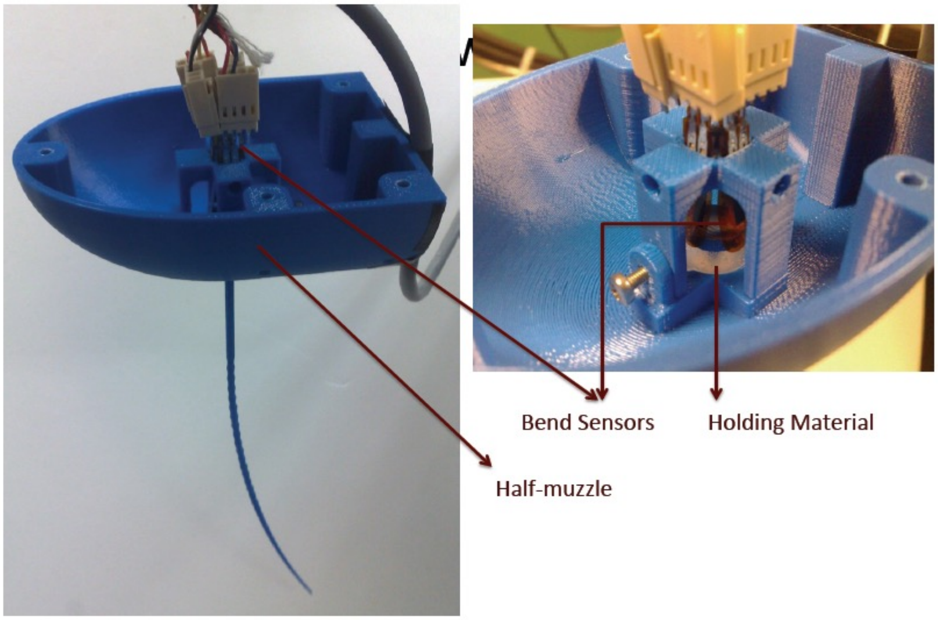

Figure 10: Model of vibrissae mounted on a specially constructed equipment containing a stress sensor to detect the deflections and vibrations of the vibrissae (preliminary work with research assistant and research staff in Singapore -- Hendrik Hans and Dr. Pablo Valdivia).

6. Conclusions

The lateral line found in most species of fish is an organ without analog in humans, and makes possible many behaviors such as obstacle avoidance, schooling and prey detection. In an effort to extend these capabilities to engineering systems, several lateral line-like pressure sensor array were constructed using innovative material sets. In each case, priority was placed on constructing a sensor array that was durable, flexible, and able to be surface-mounted on a marine vehicle.

Pressure sensor arrays were fabricated at MIT and NTU in Singapore. The two NTU sensors were constructed from commercially available piezoresistive sensor dies that were packaged on LCP and flexible PCB substrates. The array fabricated at MIT relied on a new, and unique material set that allowed for a completely flexible sensor. The array was constructed using conductive polymer strain gauges arranged in a four point probe arrangement and utilizing four independent strain-enhancing diaphragms patterned from flexible PDMS.

Overall, the experiments served as an important proof of concept for the experimental MEMS pressure sensors arrays. Tests on stalling foils demonstrated the clear capability of the sensors to detect and track flow separation through the mapping of the vortical structures forming during stall. This capability can be used to drive underwater vehciles efficiently in the presence of side currents.

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