Bio-inspired MEMS Pressure and Flow Sensors for Underwater Navigation and Object Imaging

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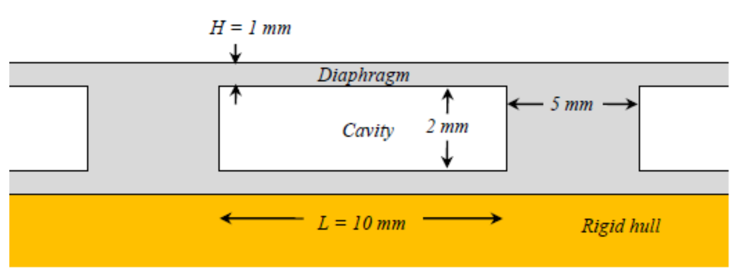
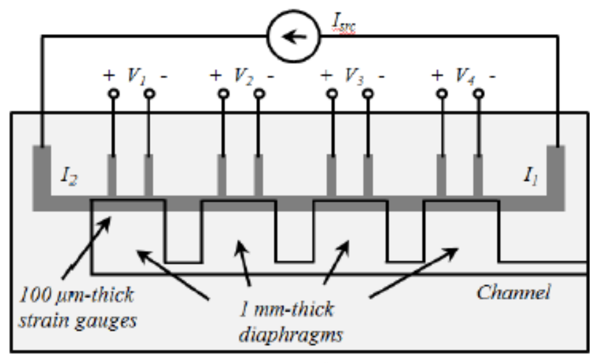
Motivation: In an effort to improve the environmental awareness of maritime devices, MEMS (Microelectromechanical System) pressure sensor arrays based on flexible polydimethylsiloxane (PDMS), liquid crystal polymer (LCP) and LCP/PDMS substrates are being developed for use on autonomous underwater vehicles (AUVs). These sensors can guide an AUV to navigate in a dark, unsteady and cluttered environment where sonar and vision-based systems fail. Microfabricated pressure sensor arrays offer a unique advantage of low-power passive sensing while their low foot-print and flexible backing make them conveniently mounted on the streamlined bodies of underwater vehicles. These MEMS arrays have individual sensors that closely mimic the biological neuromasts on the body of many fish. For instance, the blind cave fish, *Astyanax mexicanus fasciatus,* swims adeptly by solely relying on lateral-line neuromasts to generate hydrodynamic images of its surroundings. Although the lateral-line sensory system has no equivalent in current underwater vehicle detection systems, the goal of this work focuses on developing an ideal artificial lateral-line system by employing an array of MEMS flow sensors.

MIT Pressure Sensor

Array Design



Side View

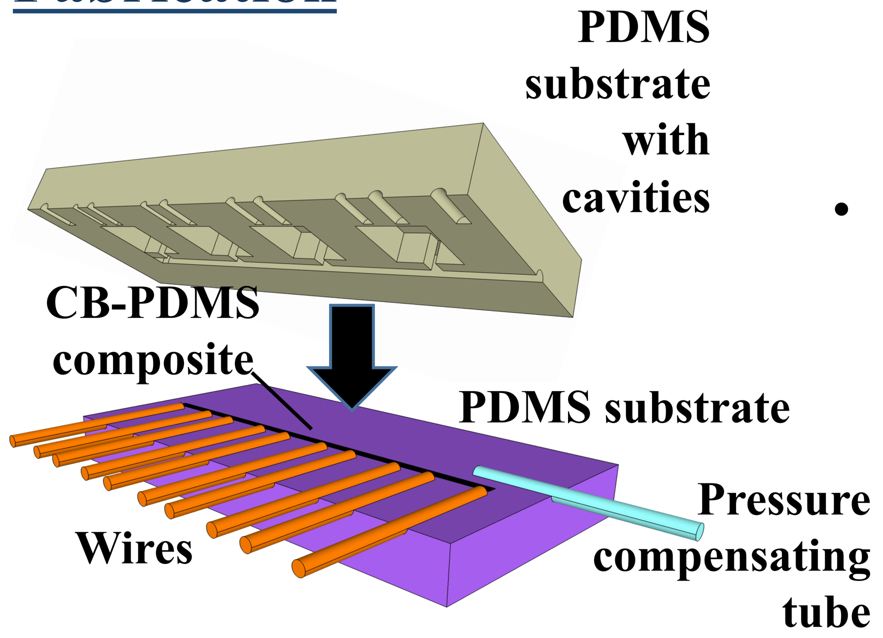


Top View

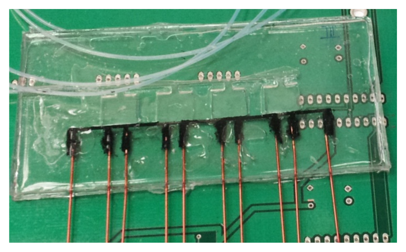
Structure: Pressure-concentrating diaphragms support conductive elastomer strain gauges whose resistances are measured using a four-point probe array.

Materials: Substrates and diaphragms are PDMS; strain gauge is a piezoresistive carbon black (CB)-PDMS composite.

Fabrication

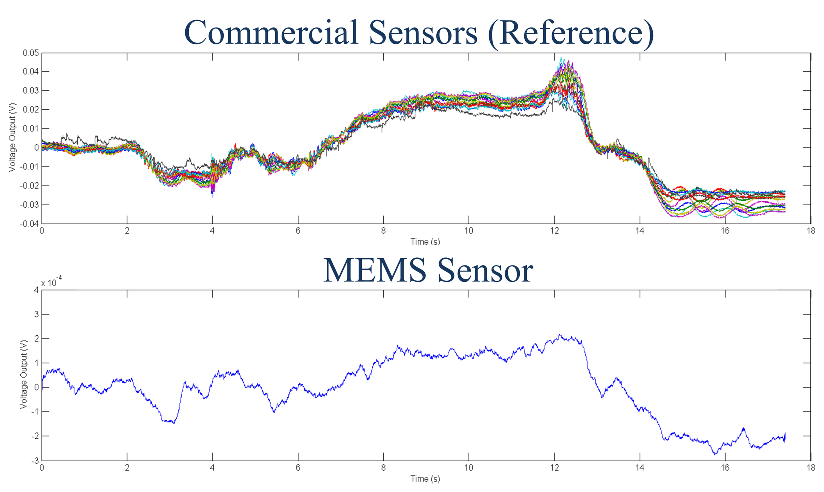


- CB-PDMS strain gauge is screen patterned onto a PDMS substrate.
- Substrates are bonded together for waterproofing.



Finished Device

Kayak Testing



When mounted on the side of a kayak for open-water tests, the pressure response of the MEMS sensor is similar to that of a somewhat-nearby reference sensor.

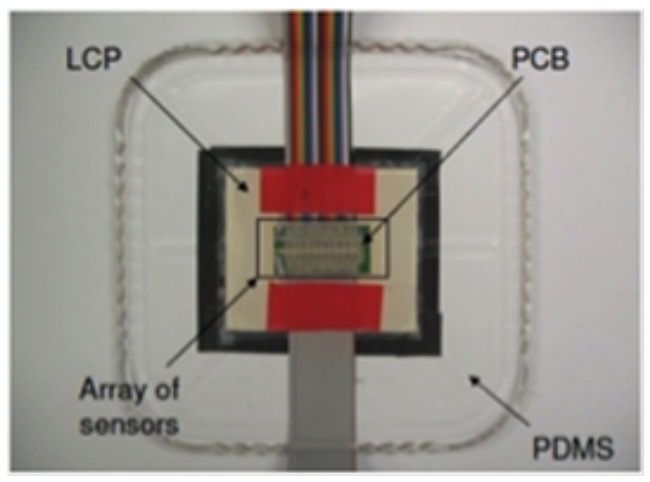
Conclusions

- Sensor is functional in an uncontrolled environment
- Sensor can be mounted on a doubly-curved surface
- Sensor resolution is ≈ 10 Pa
- Array power dissipation is ≈ 2μW per sensor

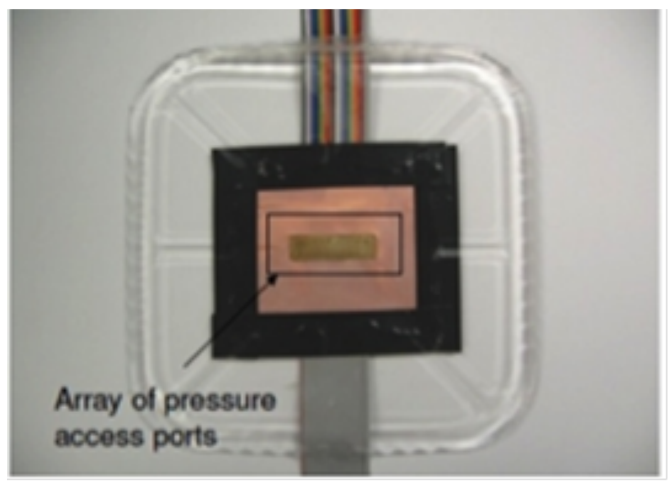
Singapore Pressure Sensor

An array of 2 × 10 silicon piezoresistive pressure sensors were fabricated on flexible LCP substrates and were encapsulated in PDMS before mounting on the kayak. The array of sensors were tested in a reservoir for various pressure signals.

Fabrication



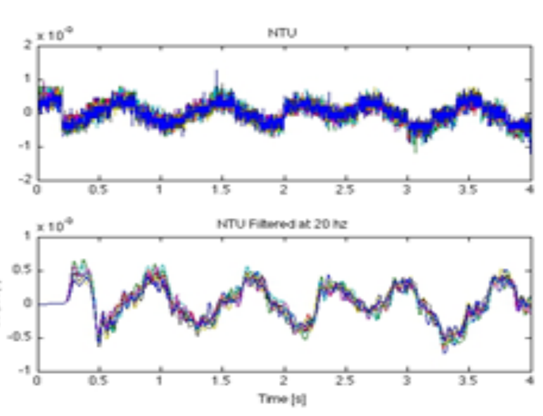
Backside of PCB sensor array



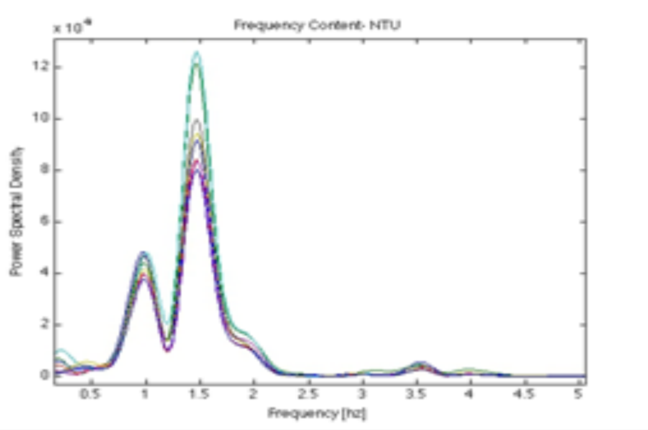
Front of PCB sensor array

Kayak Testing: Commercial vs. MEMS

Underwater Testing



Pitching Test

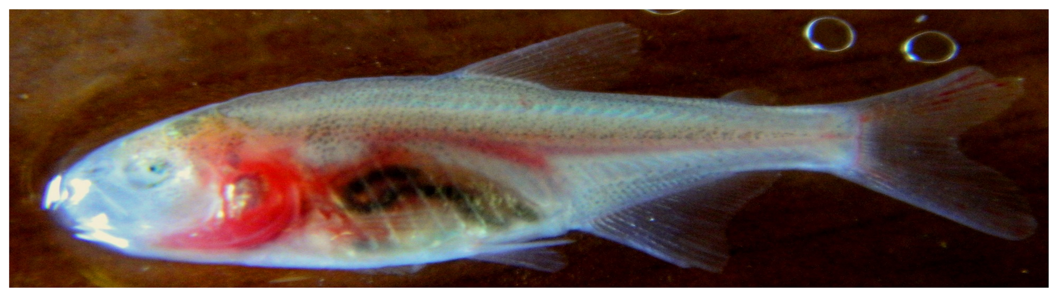


Power Spectrum of Pitching Test

During the pool test, results show that the MEMS sensors were able to generate the same output signals as the commercial sensors.

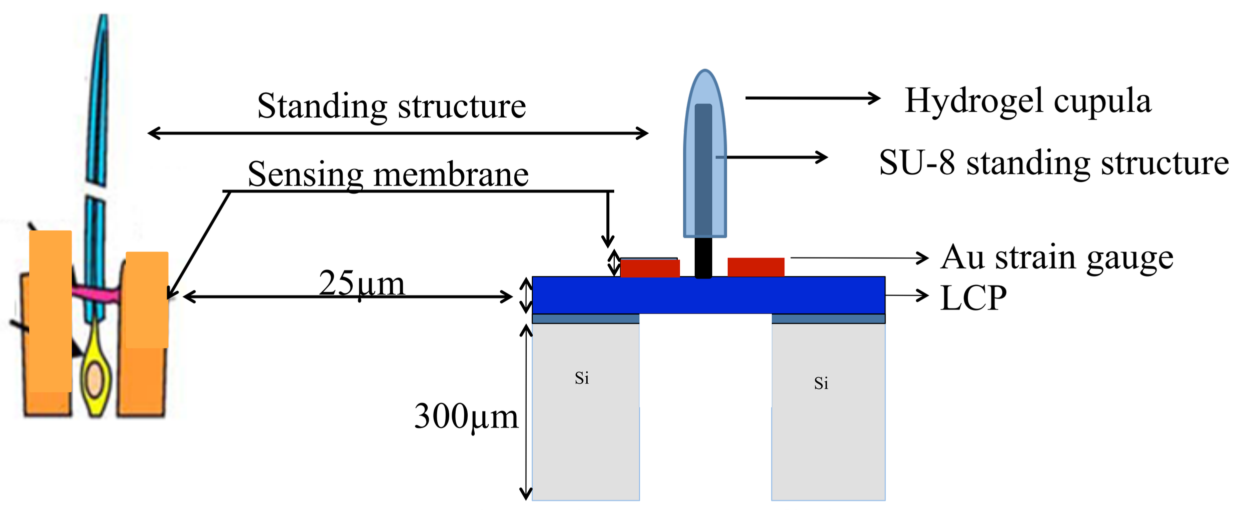
Singapore Flow Sensor

This device consists of a LCP diaphragm and an SU-8 standing pillar resembling the cupula of the fish sensor. Hydrogel material (having same Young's modulus as cupula and also photo-patternable) could be used to encapsulate the pillar. The sensors demonstrate a detection limit as low as 0.46 Pa – capability that matches with that of the fish in detecting the flow pressure.

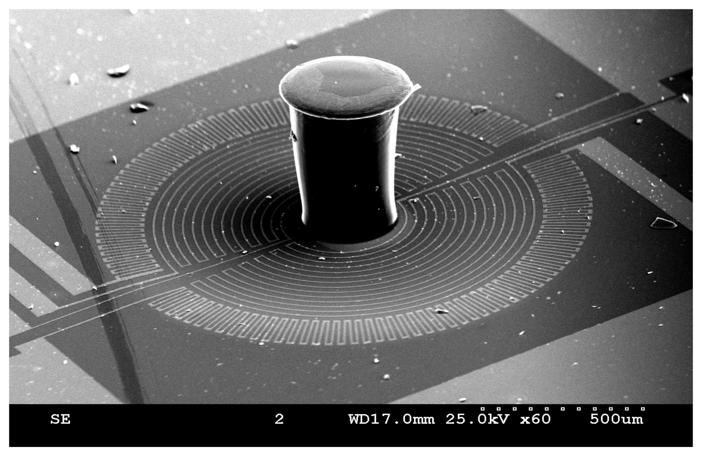


A photograph of blind cave fish - Astyanax mexicanus fasciatus. Due to survival in dark deep caves, this fish developed an atrophied eye and pale pink skin.

Biomimetic Sensor Design



An analogy between biological superficial neuromast and an artificial MEMS neuromast.



SEM image of SU-8 pillar on Si membrane. A circuit is patterned on diaphragm using metal strain gauges.

Conclusions

- The sensors developed can measure air and water flow velocities with a good sensitivity of 64 (μV/V/Pa) and 12.6 (μV/V/Pa), respectively.
- LCP has a very low moisture absorption coefficient and low chemical attack, and therefore offers high reliability.

References:

- F. M. Yaul, "A flexible underwater pressure sensor array for artificial lateral line applications," Master's thesis, Massachusetts Institute of Technology, September 2011.
- A. G. P. Kottapalli et. al., "Liquid crystal polymer membrane MEMS sensor for flow rate and flow direction sensing applications," 2011, *J. Micromech. Microeng.* 21, 085006 (11pp)

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