Nature-Inspired Biomimetic MEMS/NEMS Sensors for wireless Sensing

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MIT Sea Grant College Program
Massachusetts Institute of Technology (MIT)

Background

Assistant Professor at RUG 2018 - present
Principal Research Scientist 2015- 2017
Postdoctoral Associate 2014-2015
Associate Scientist at MIT 2013-present

PhD 2010-2013

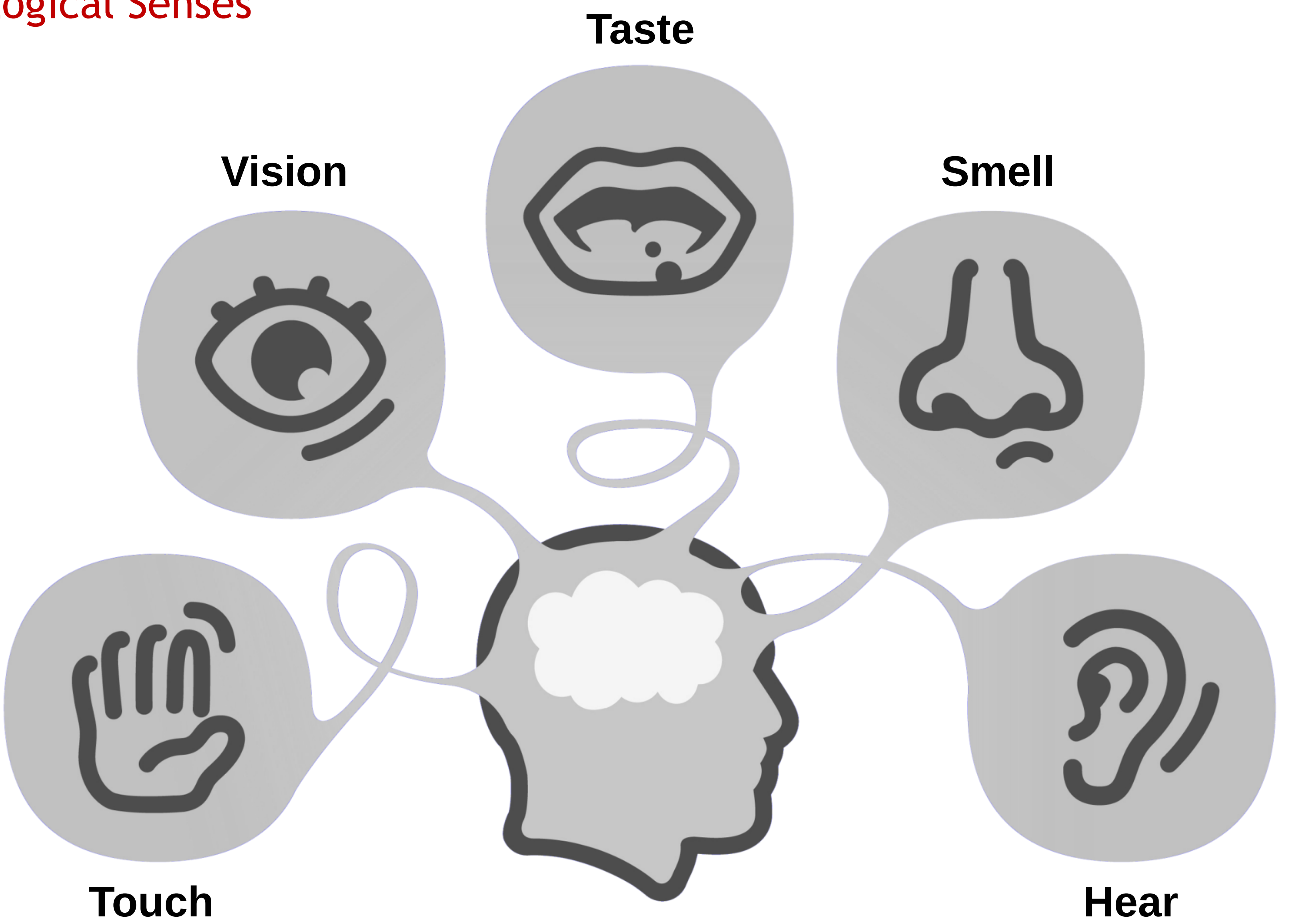
Singapore-MIT Alliance Graduate Fellowship
Nanyang Technological University (NTU) and
Massachusetts Institute of Technology (MIT)

Masters in Technology (M.Tech) Solid State Technology 2007-2009

Masters in Physics (M.Sc) with Hons. (Photonics, Specialization) 2005-2007

B.Sc (Physics) with Hons. 2002-2005

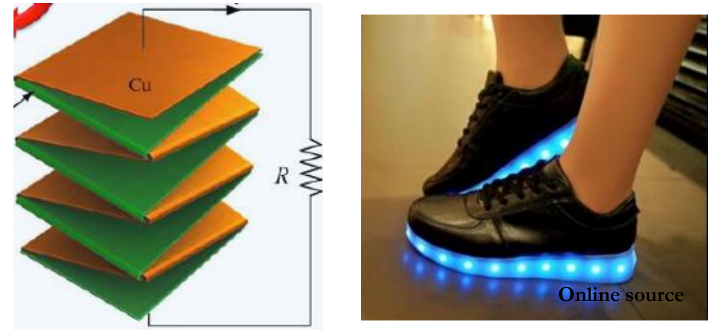
Biological Senses



http://udel.edu/~spfefer/art307/project3/

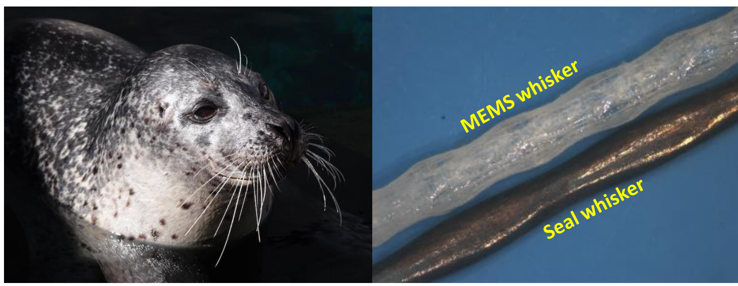
Biomimetic Micro/Nano Electromechanical Systems (MEMS/NEMS)

Biomimetic MEMS flow Sensors inspired by the superficial neuromasts in blind cavefish

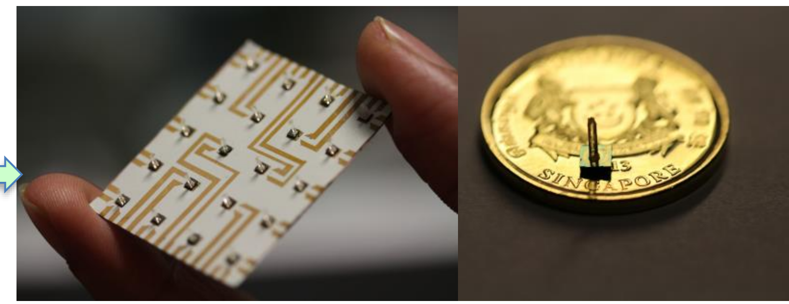


Origami-inspired energy harvesters for wearables

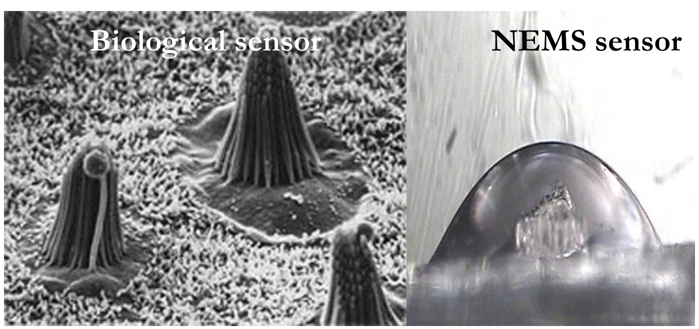
Design and fabrication of MEMS/NEMS sensors



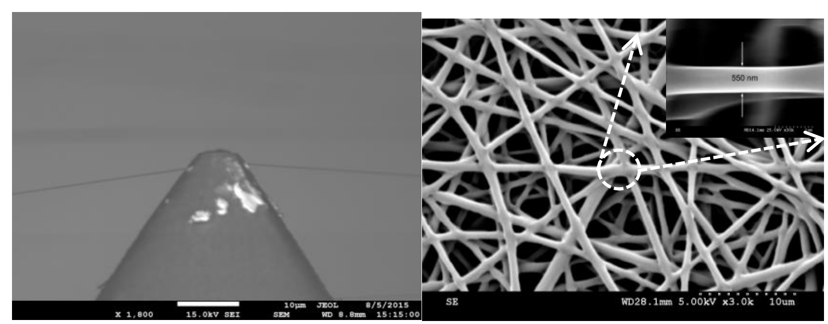
Harbor seal whisker inspired MEMS flow sensors to reduce vortex-induced vibrations



Artificial smart skin of flexible and self-powered MEMS flow sensors



Ultrasensitive artificial NEMS ciliary bundles inspired by mechanotransduction in biological sensors in nature



Electronic sensing materials for flexible, wearable and stitchable sensors

Neuromast Inspired Flow Sensors for Fish-Like Underwater Sensing

Background: Bioinspiration – Blind cavefish

Astyanax mexicanus fasciatus

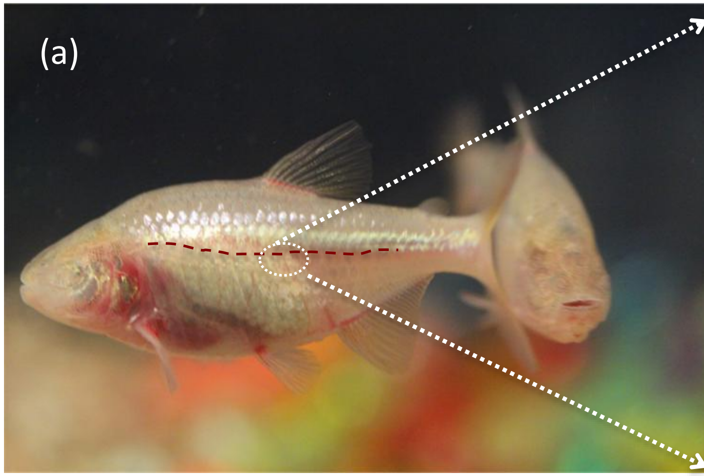
**Hydrodynamic imaging: Blind cave fish in a tank with lego obstacles*

Energy efficient maneuvering: Fish performing Karman gaiting behind a D-shaped cylinder

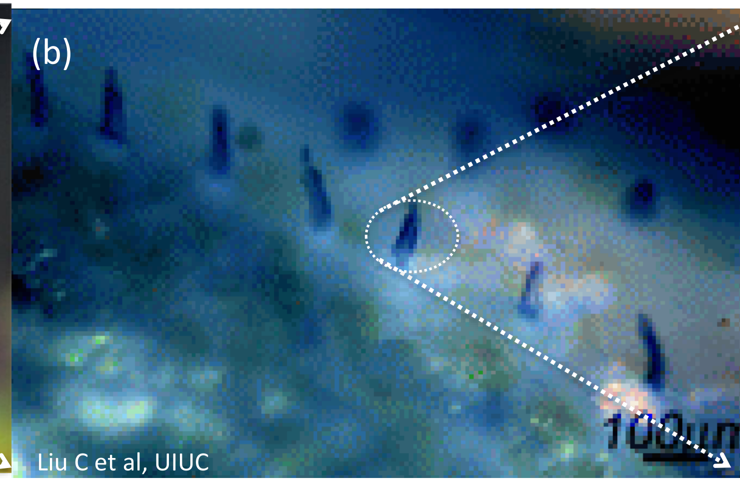
Control and maneuvering: Fish escape response through flow Sensing

Superficial neuromast (SN) sensors

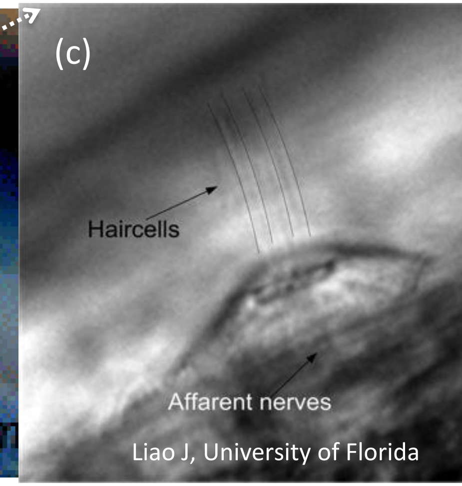
Superficial neuromasts and flow sensing



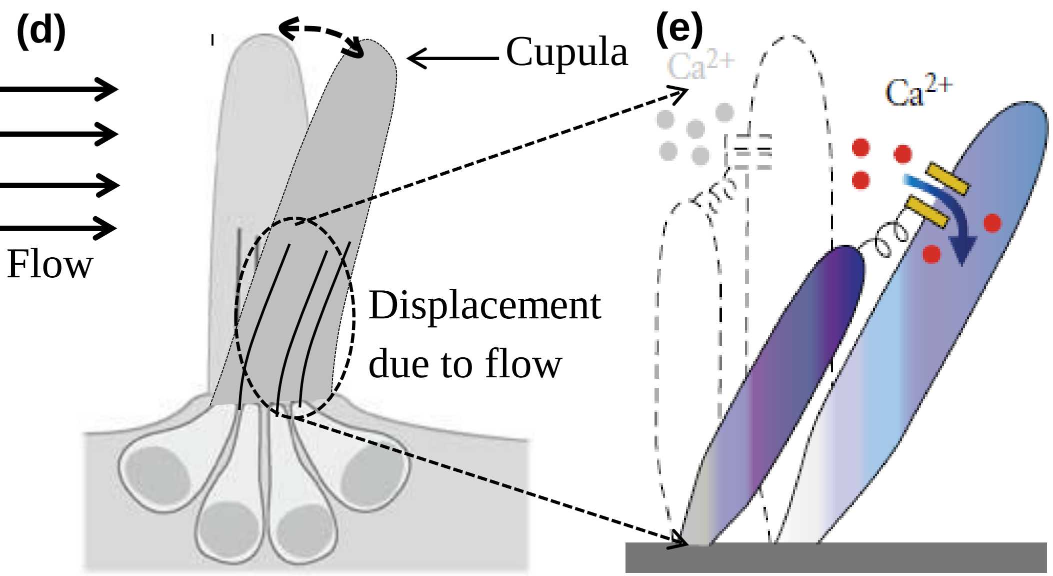
(a) Bio-inspiration: Blind cave fish



(b) SEM image of the lateral-line



(c) Single biological neuromast



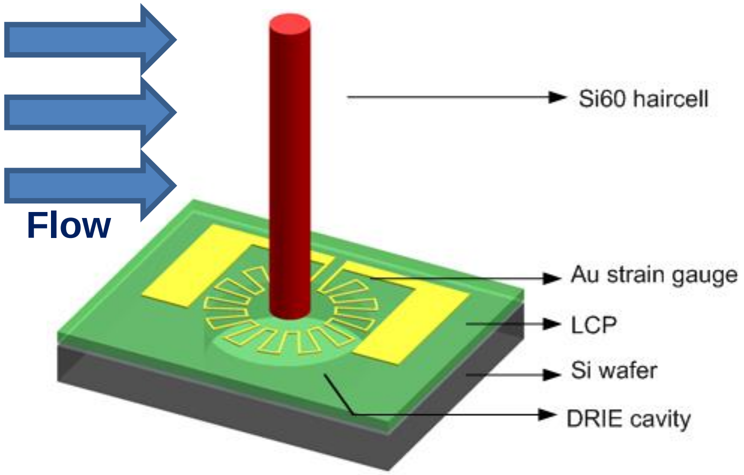
(adapted from Van Netten , *J. Comp.Physiol.*, 2008)

adapted from Liu C, *ERASIP J. Appl. Signal Process.*

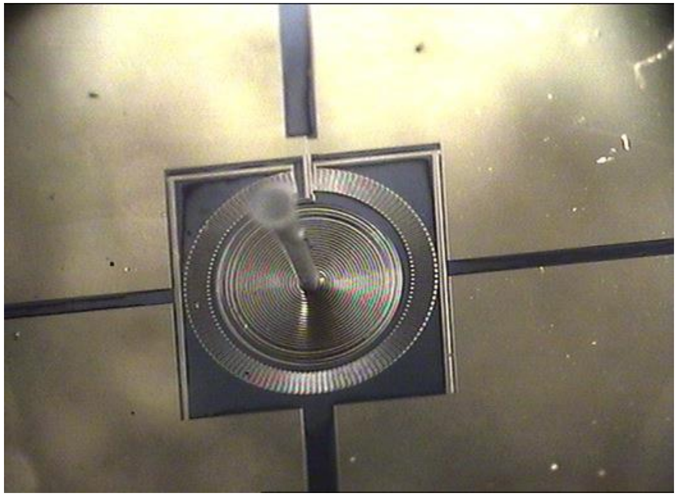
(d) and (e) Sensing principle

- Located on the surface of the skin
- Cupula couples flow to the embedded haircells & increases drag force
- Tiny haircells- key sensing elements
- Measure relative flow between the body and the surroundings.
- Hydrodynamic flow mapping on the entire body

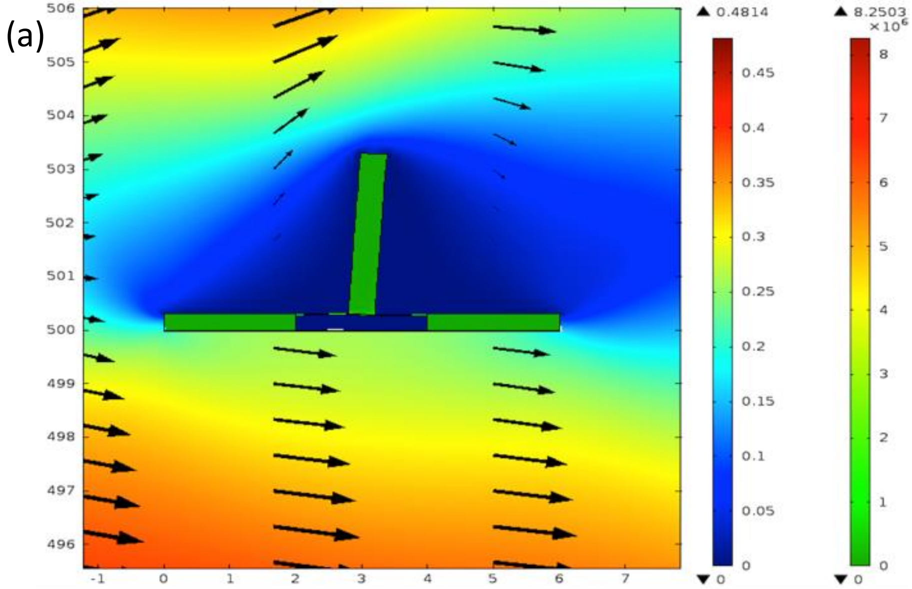
LCP haircell sensor design

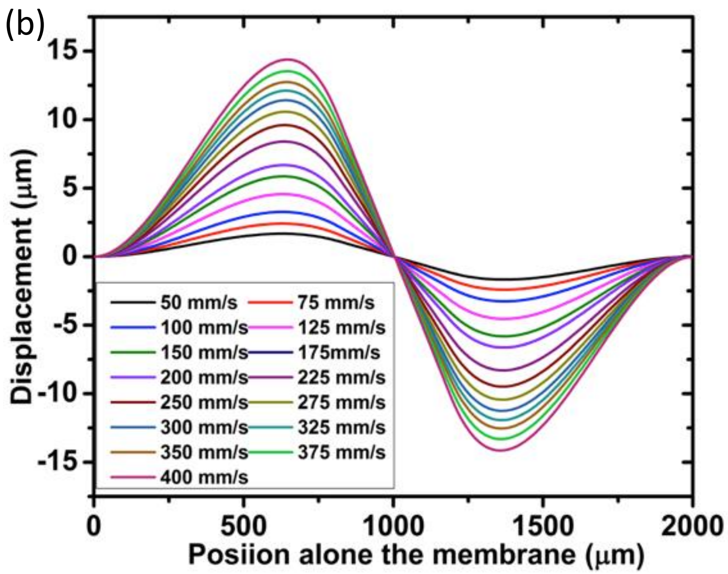


Structure of LCP MEMS Haircell sensor



SU-8 haircell on LCP membrane



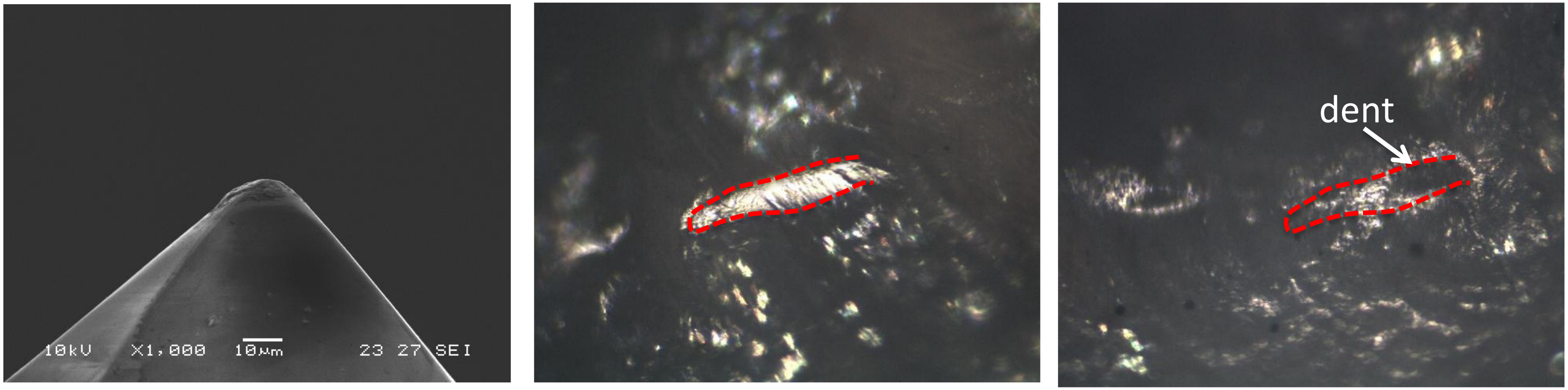


COMSOL finite element simulation results (a) membrane displacement in response to a water flow velocity of 0.5m/s (b) displacement profile of the membrane for various water flow velocities

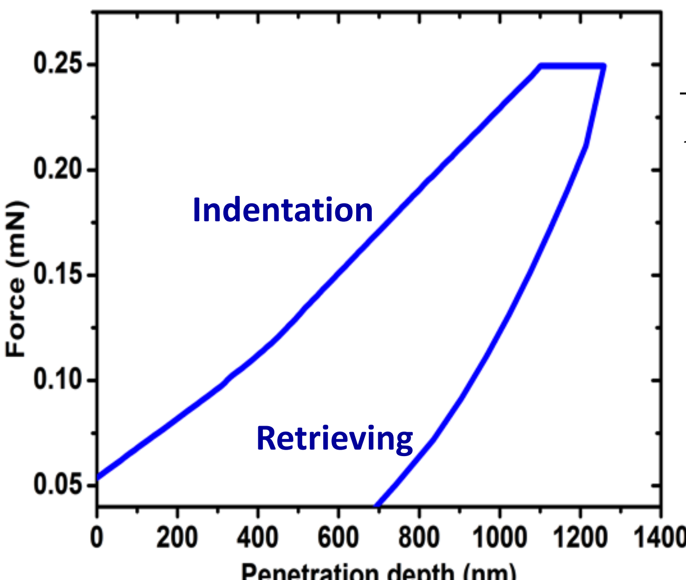
The high-aspect ratio haircells reach beyond the flow generated by the boundary layers and results in enhanced sensitivity

Biomimetic materials for cupula

Biological cupula



SEM and optical images of (a) Cono-spherical tip used for indentation. Cupula surface (b) before and (c) after indentation



Nanoindentation analysis on biological cupula

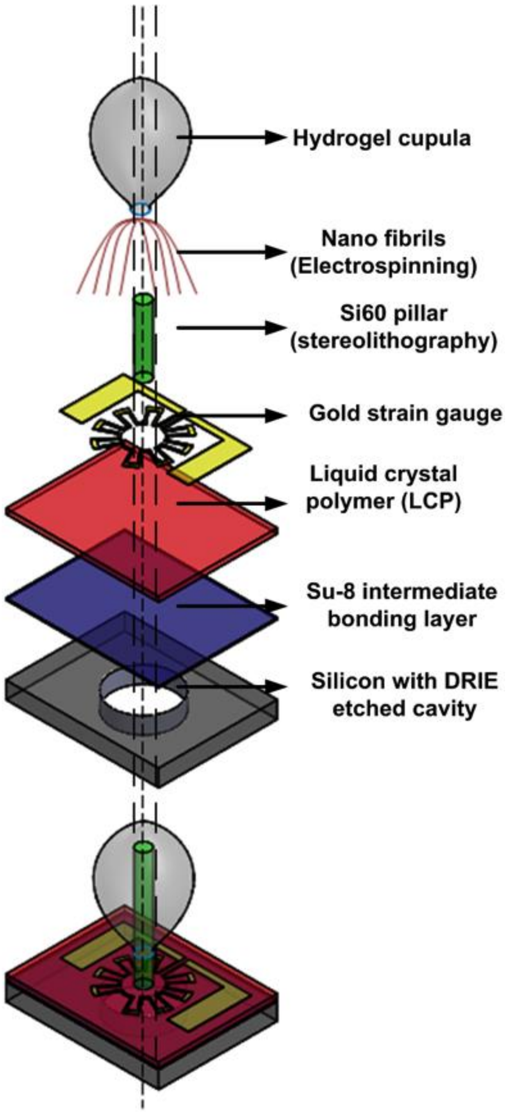
$$\frac{1}{E_r} = \frac{1-\upsilon_i^{\,2}}{E_i} + \frac{1-\upsilon_s^{\,2}}{E_s}$$

subscript *i* and *s* refer to indenter and sample materials, and *υ* refers to Poisson's ratio, E_r reduced modulus (the combined modulus of the tip and the sample)

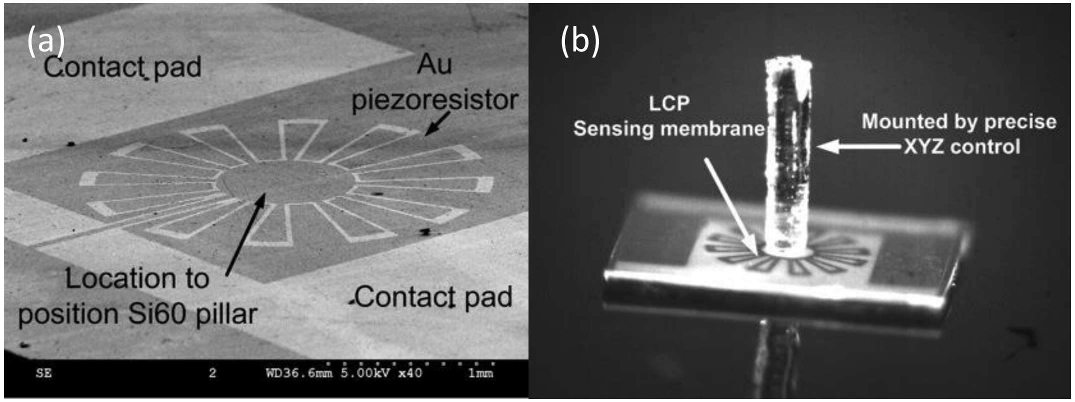
- Hardness = 40kPa
- Young's modulus (*E*) = 138kPa
- Observed *E* is much higher than the vales reported in the past
- Sample preparation methods resulted in higher *E* value

Biomimmetic Artificial Neuromast Sensor

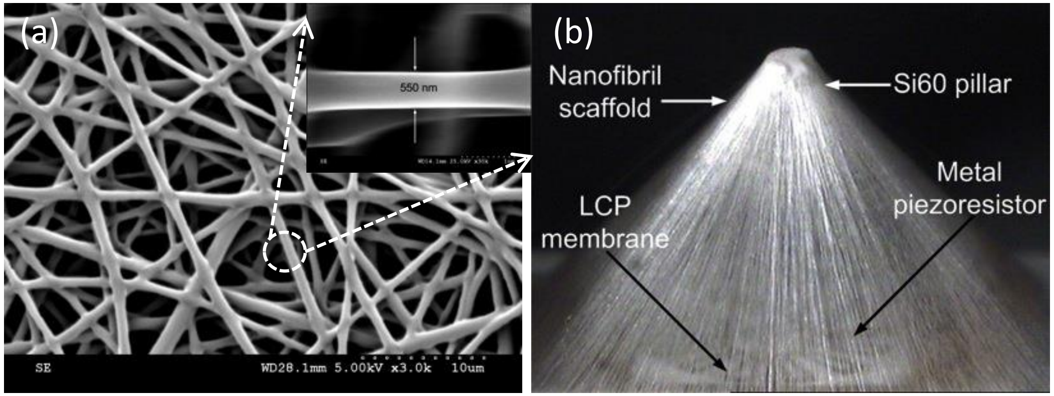
Sensor fabrication



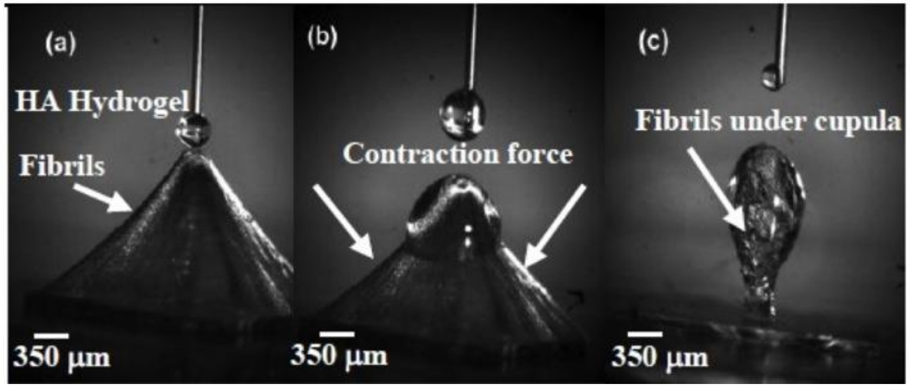
A schematic showing the exploded view of the fabrication scheme designed to form MEMS artificial neuromast sensor



(a) LCP sensing membrane (b) Naked haircell sensor



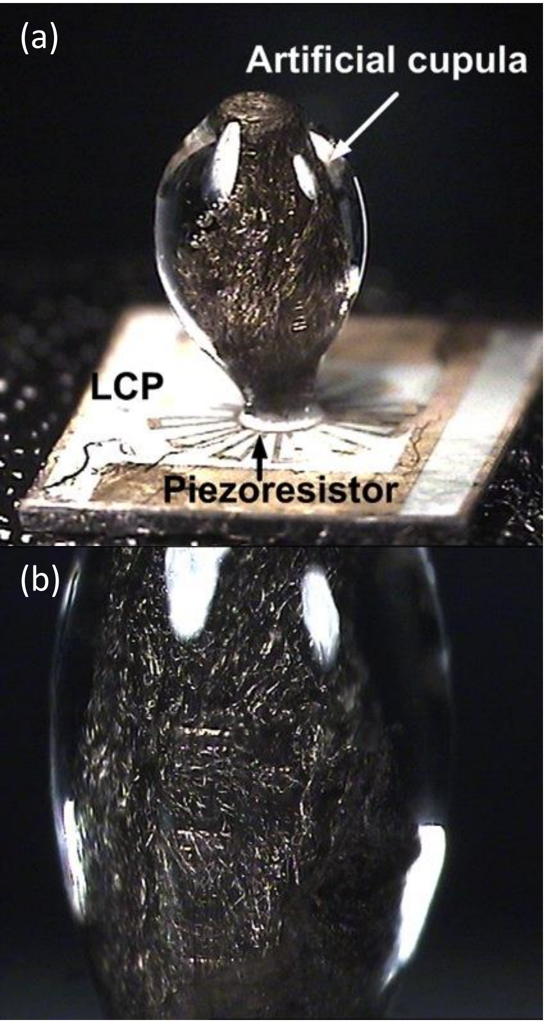
Electrospinning to form cupular fibrils (a) nanofiber optimization (b) Electrospun scaffold



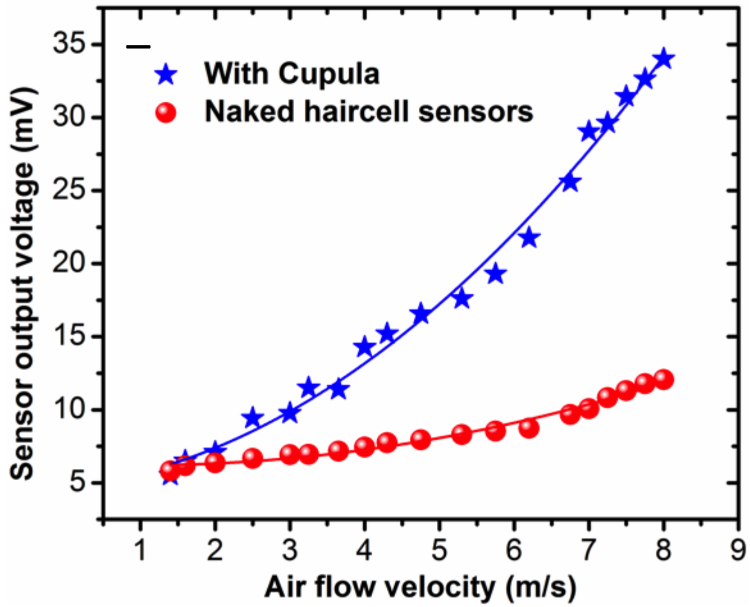
HA-MA Hydrogel drop-casting process

Flow sensing abilities of the MEMS neuromast

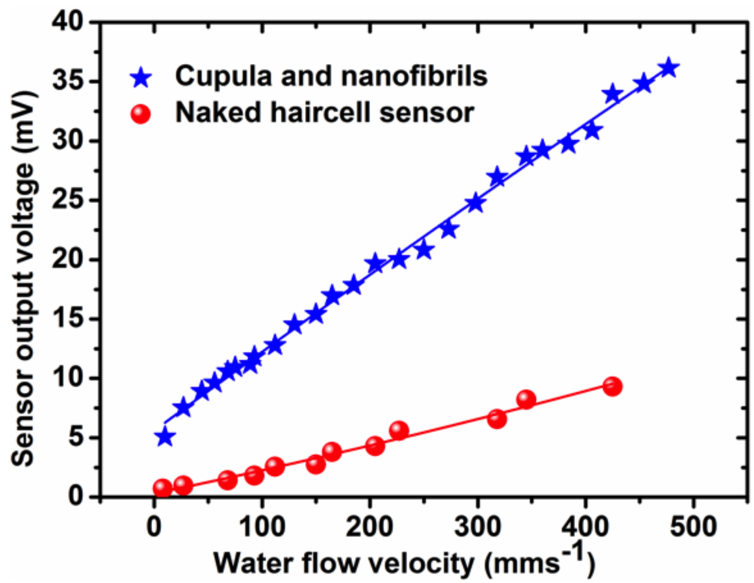
Experimental Results



Microscopic images of (a) MEMS Artificial neuromast flow sensor (b) Zoom-in view showing the enapsulated cupular fibrils



Wind tunnel flow calibration results



Water tunnel flow calibration results

Achievements

- Ultrahigh sensitivity
  - -4.5mV/(m/s) for air flow
  - - 5 times enhancement
  - -0.08mV/(mm/s) for water flow
  - -3.5 times enhancement
- Threshold detection limits
  - -0.01m/s for air flow
  - -20mm/s in water flow
- Enhanced accuracy
  - -VIV reduction
  - - Reduced turbulence
- Robustness
  - - Reliable materials
  - - 20m/s air flow
  - - 3m/s water flow

$$\left(\frac{F_{cupula}}{F_{hair}}\right) \approx \left(\frac{H_{cupula}}{H_{hair}}\right)^{4/3} \left(\frac{D_{cupula}}{D_{hair}}\right)^{2/3}$$

- F – drag force
- H – height
- D – diameter
- Subscript c – cupula and h– haircell

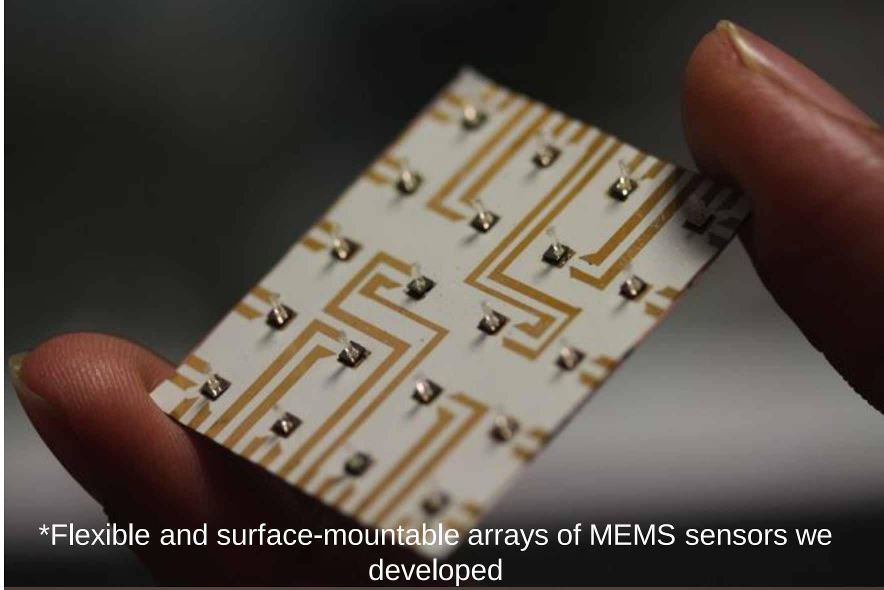
*Ajay Kottapalli et al, Asia Materials (Nature Publication Group), 2017, **9**, e440

Zero-Powered Flow Sensors

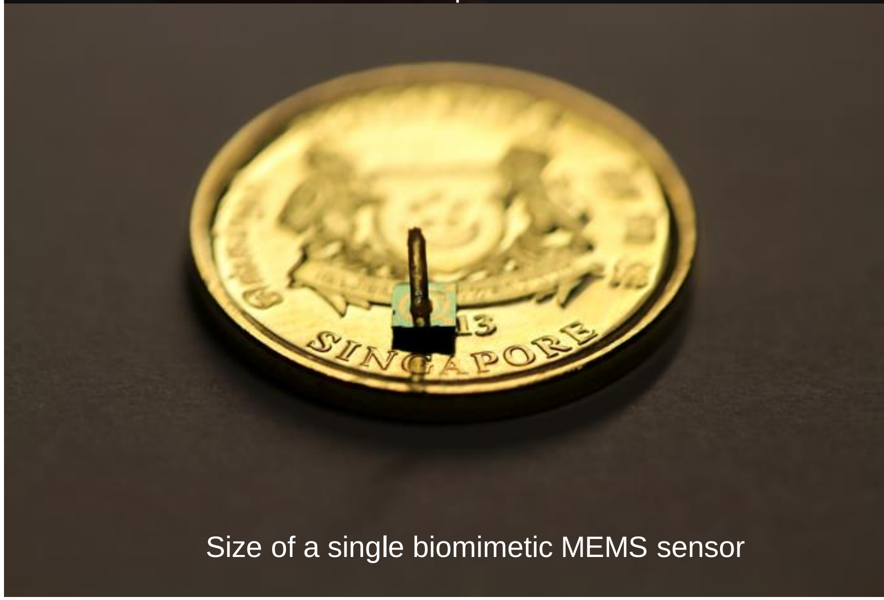
- Fundamentally, it is possible to translate complex mechanosensory sensing principles found in nature onto an artificial sensory platform using MEMS technology

- MEMS/NEMS sensors can be fabricated with various structural configurations and materials and at the dimensions of biological sensors

- Features of our MEMS flow pressure sensors
  - Ultrahigh sensitivity
  - Extremely low threshold detection limits
  - Self-powered
  - Miniaturized
  - Robust and reliable
  - Low cost
  - Packaged in to flexible surface-mountable arrays
  - Biomimetic signal amplification and noise rejection strategy



*Flexible and surface-mountable arrays of MEMS sensors we developed



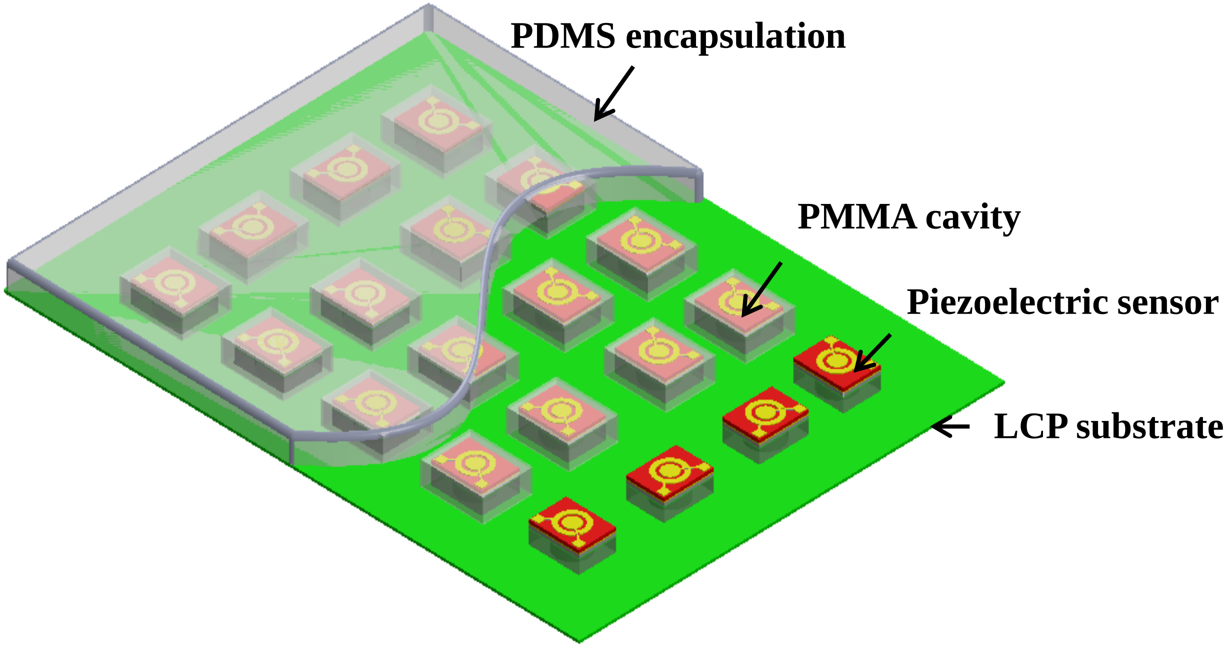
Size of a single biomimetic MEMS sensor

*Ajay K, Asadnia M, Miao J M and Triantafyllou M, (2013) *US Patent* Application No.: 61/541,232
Asadnia M, Ajay K, Miao J M and Triantafyllou M S (2015) *Royal. Soc. Interface.*. ***13,*** *pp. 3818-3925*

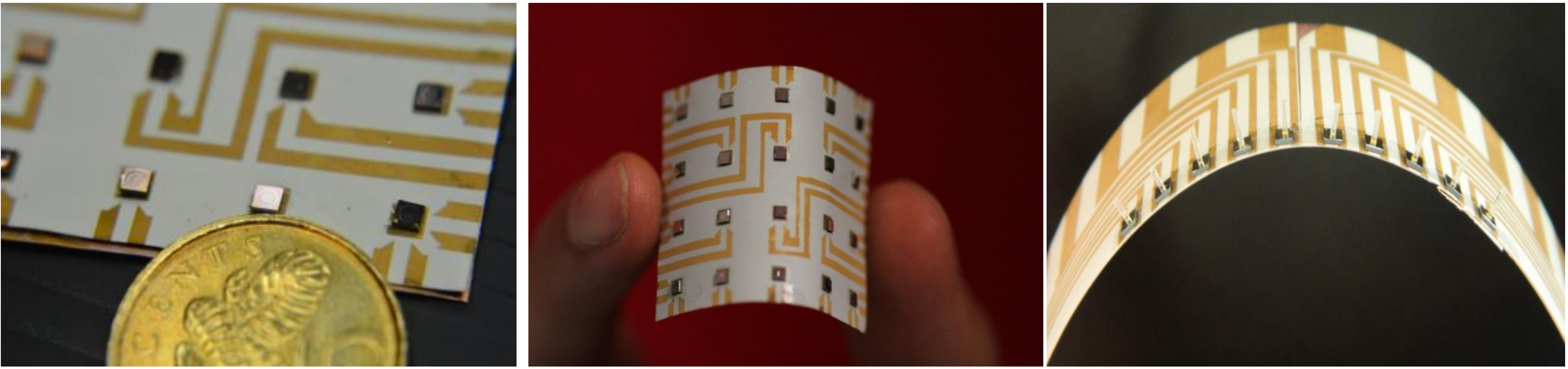
Packaging

Key points:

- Flexibility
- Surface mountable
- Under water protection
- Stability in harsh environment

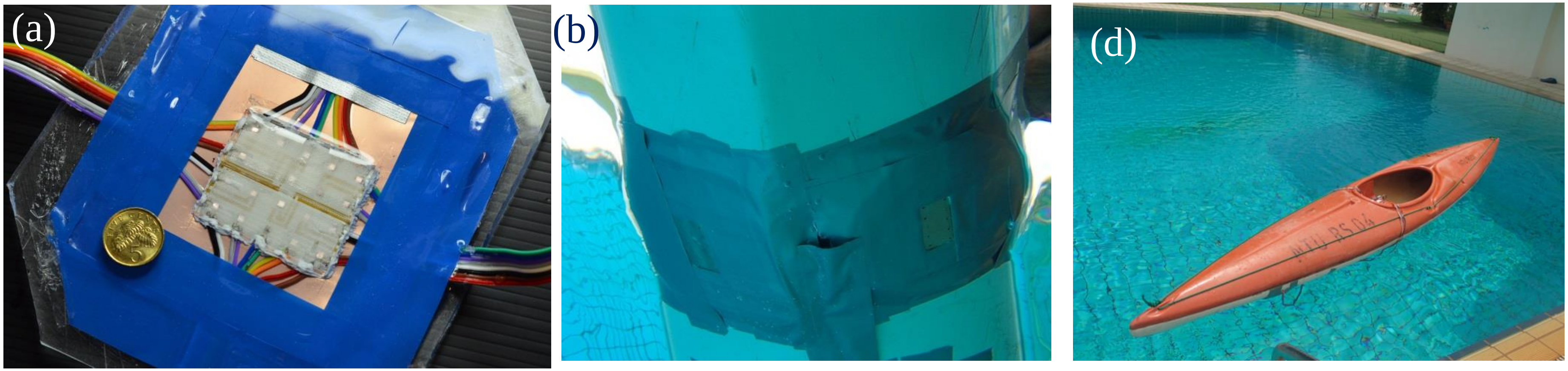


Schematic view of the array of 4 × 5 sensors

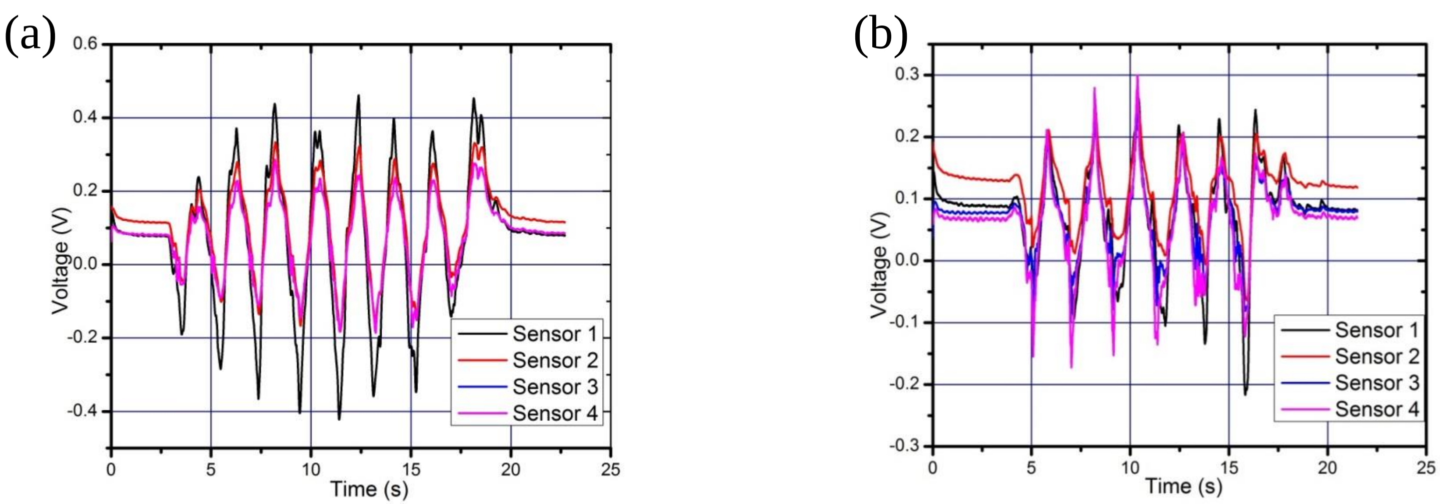


Array of 4 × 5 of the piezoelectric sensors mounted on flexible LCP

Real-time underwater sensing



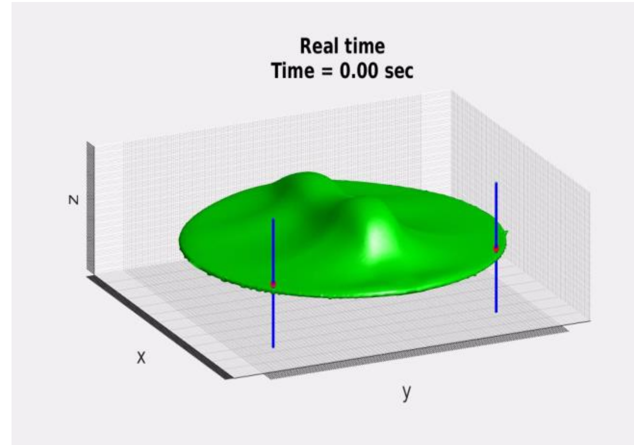
(a) Array of 4 by 5 of proposed (b) The sensors were surface mounted on the kayak and submerged in
(b) water for experiment



(a) A signal generated by manually lifting and pushing the kayak up and down in water (b) A signal generated by rolling the kayak side to side in the water

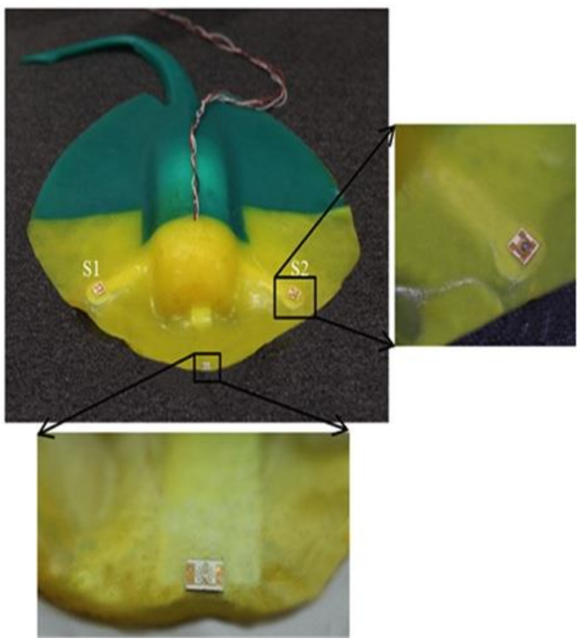
Mohsen. Asadnia, et al. IEEE sensor journal, 2013

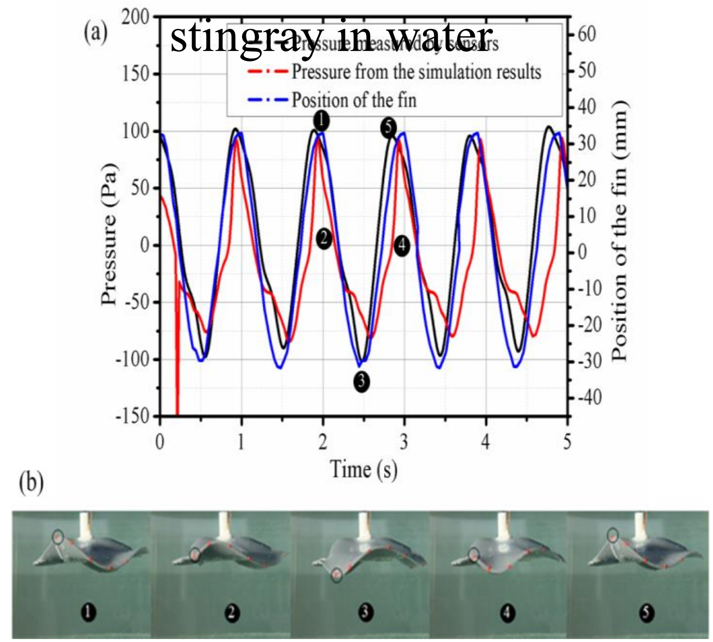
Sensing Real-Time Hydrodynamics on a Robotic Stingray



3-dimensional simulation of the robotic stingray in water

Robotic stingray



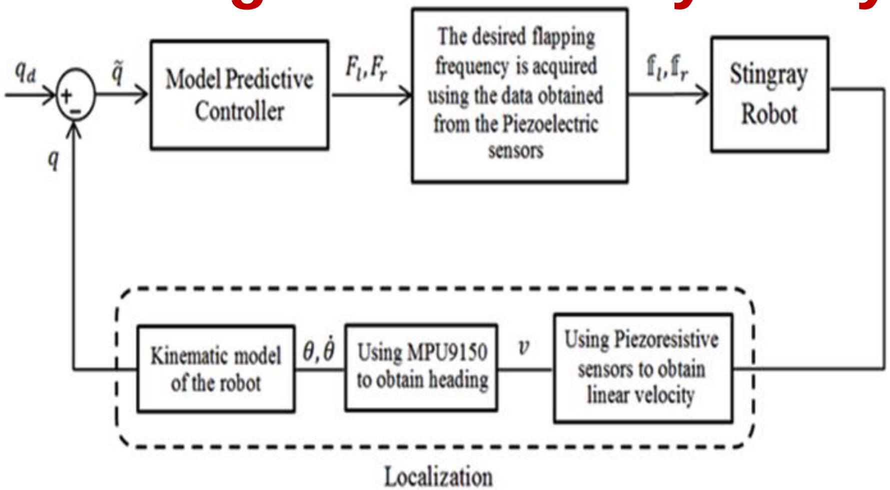


Sequence of images taken as the stingray flaps at a frequency of 1Hz

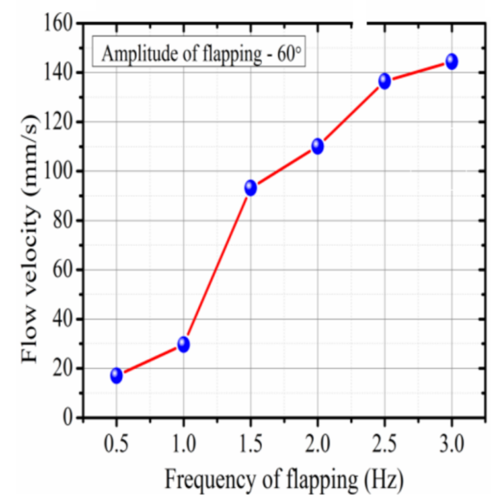
MEMS pressure and flow sensors mounted on the robotic stingray (Courtesy: Pablo v Alvarado)

Asadnia M, et al. *Bioinspir. Biomim. 2015*

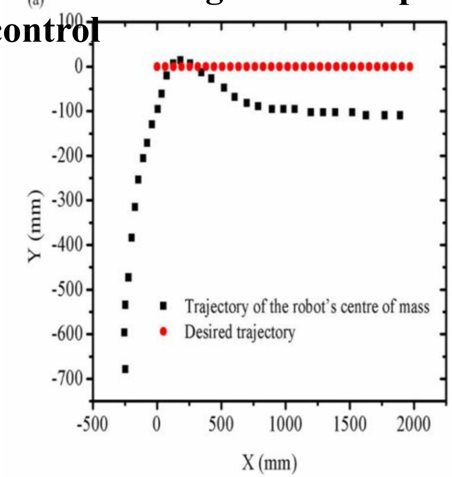
Sensing Real-Time Hydrodynamics

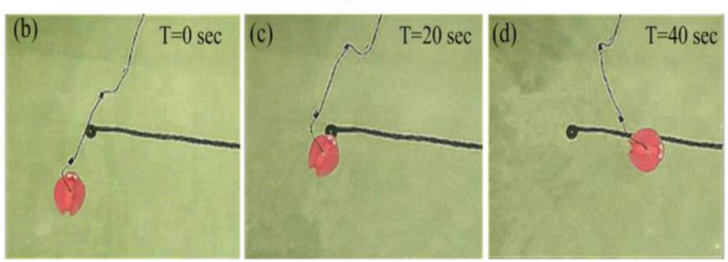


The block diagram of the proposed feedback control

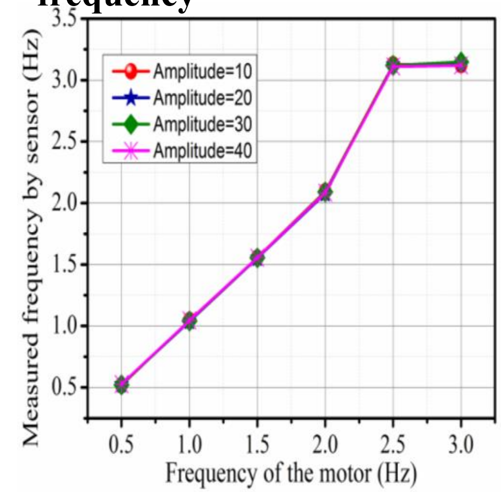


velocity of propagation of the robot with respect to fin flapping frequency





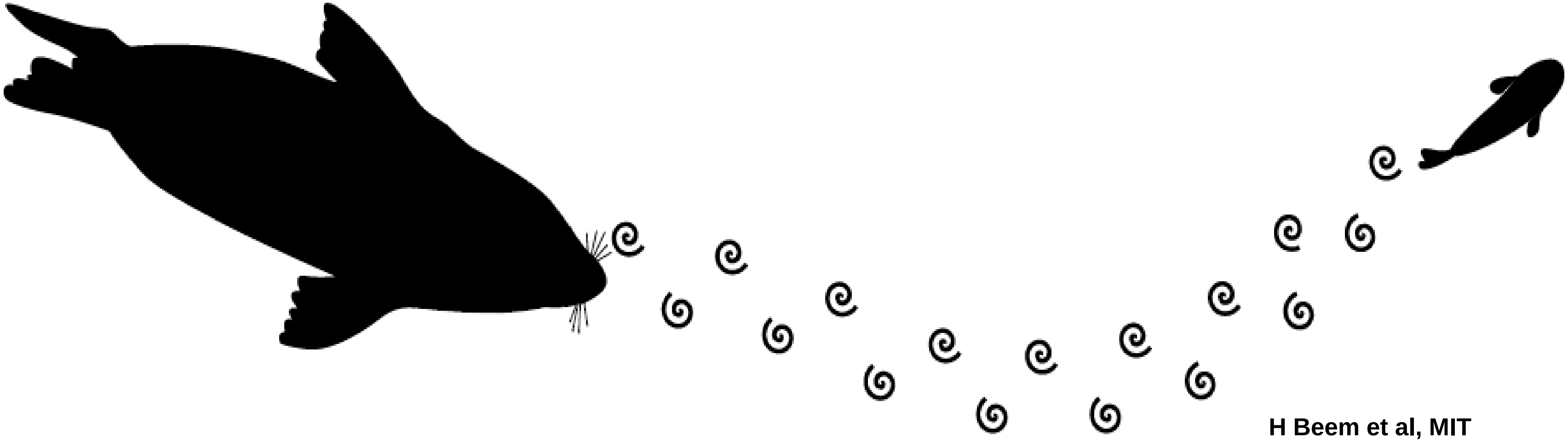
(a) Trajectory of the robot's center (b) Snapshot of the robot at different time instances



Comparing the measured frequency and the actual frequency of the fin

Asadnia M, et al. , *Bioinspir. Biomim. 2015*

Seal Whisker Inspired Flow Sensors

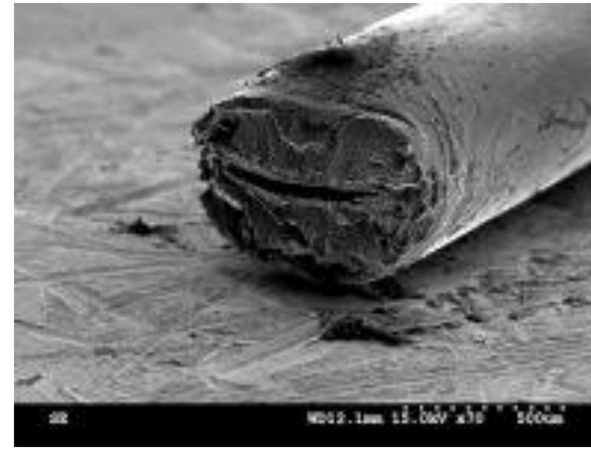


H Beem et al, MIT

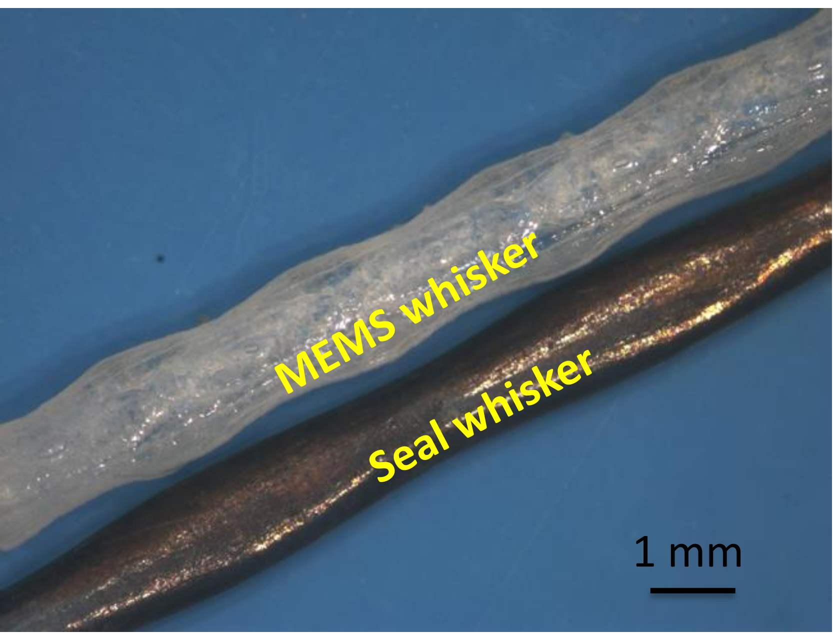
Seal-whisker and flow sensing

Harbor Seal (*Phoca Vitulina*)

Microscopic image showing the Undulatory whisker geometry



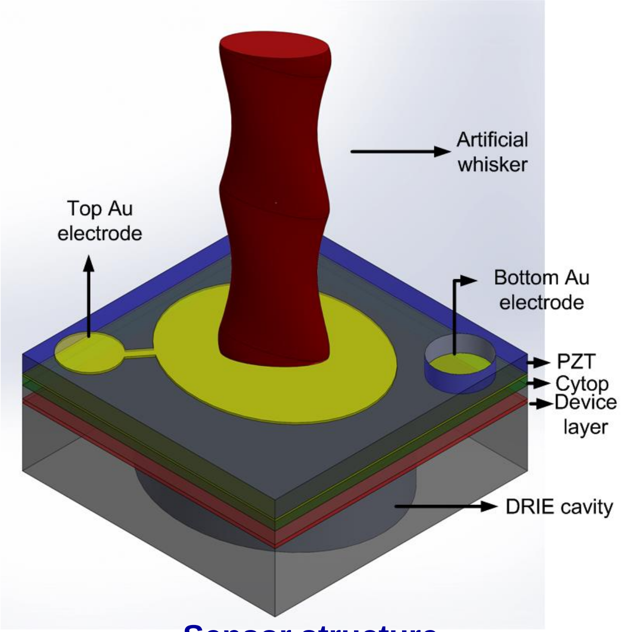
Cross-section of the whisker reveals no muscle



Artificial micro-whisker with undulatory geometry

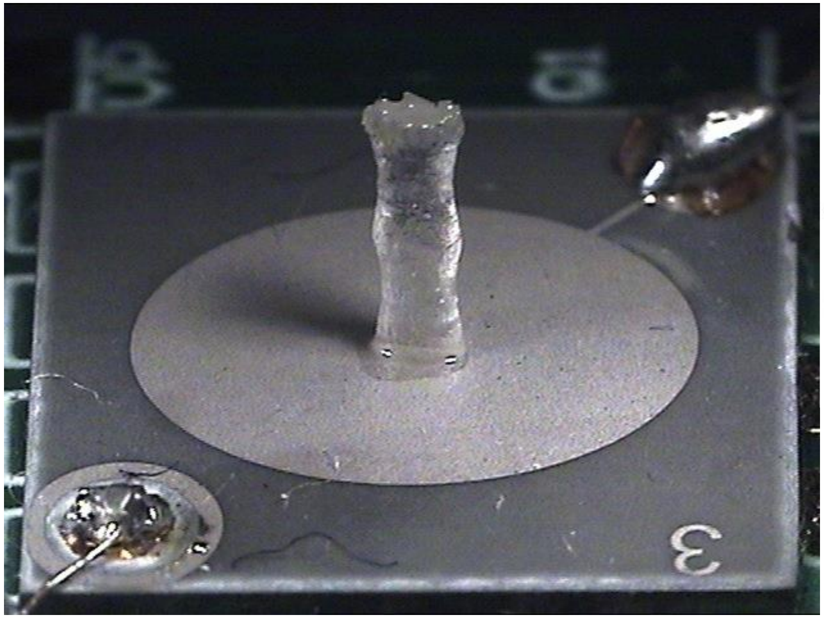
- Complex 3D geometry with elliptical cross-section
- Undulations on major and minor axis
- Capable of detecting the wake of a fish up to 35s after the fish has passed.
- Unique undulatory geometry is believed to have a contribution towards reducing vortex-induced vibrations experienced
- Achieve ultrahigh sensitivity 245 μm/s

Seal-whisker inspired MEMS flow sensor

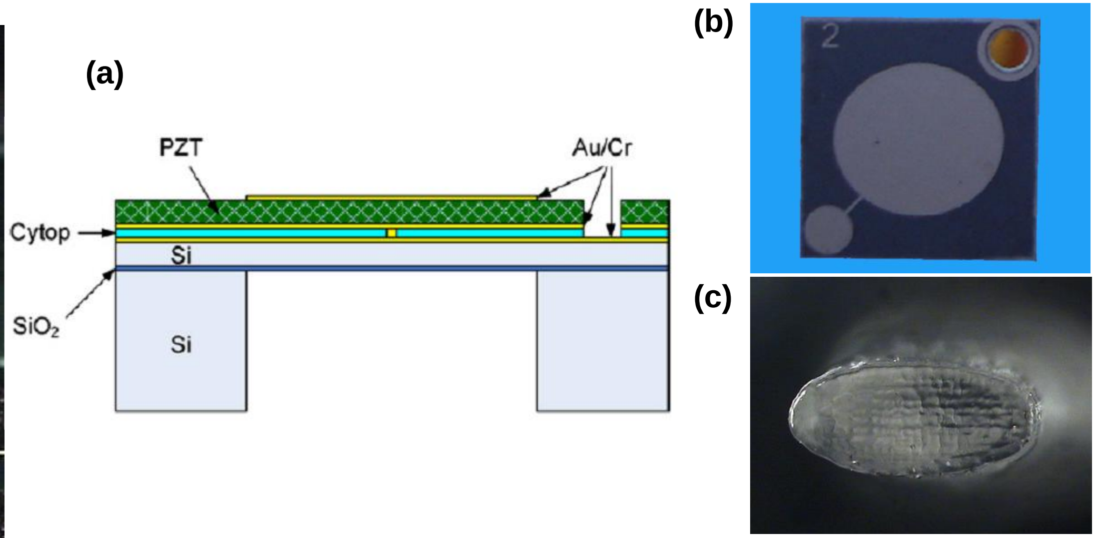


Sensor structure

- Piezoelectric sensing membrane
- Micro-whisker fabricated by stereolithography
- Micro-whisker structure interacts with flow.
- Flow variations cause displacement of the whisker which in turn causes the PZT membrane to bend
- Charges generated by membrane bending are calibrated to flow velocity that the whisker faces



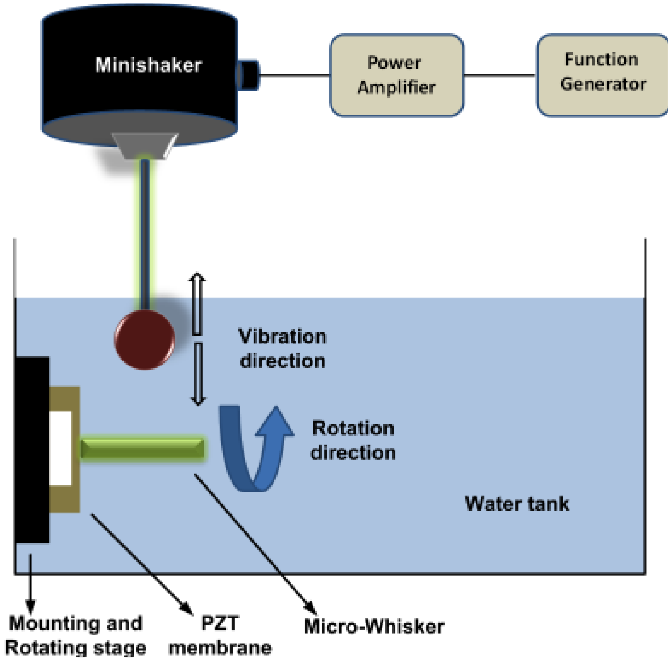
Optical microscopic image of the sensor



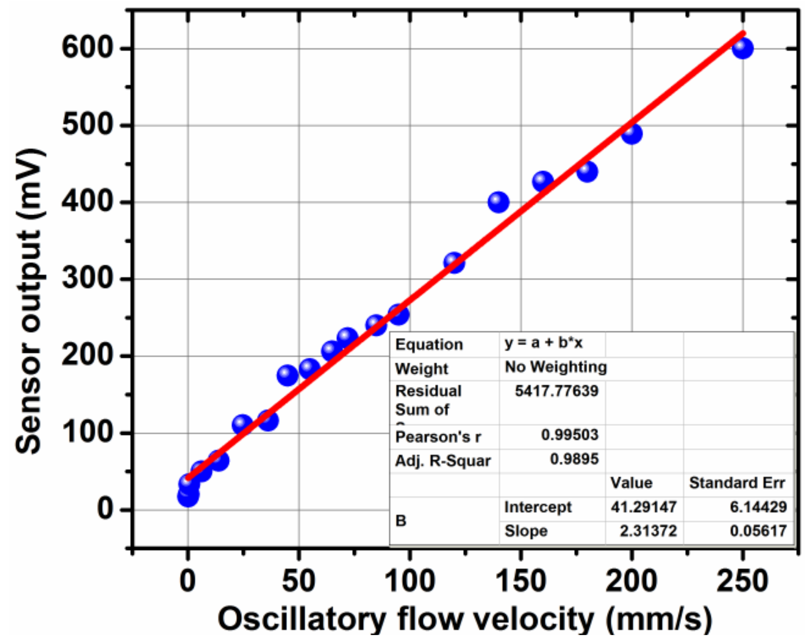
Sensor fabrication process (a) Various sensing layers in the membrane (b) Top-view of the PZT membrane (c) Flat mountable base of the whisker

A. Kottapalli, M. Asadnia, J. M. Miao and M. S. Triantafyllou, *IEEE MEMS Conference*, 2014

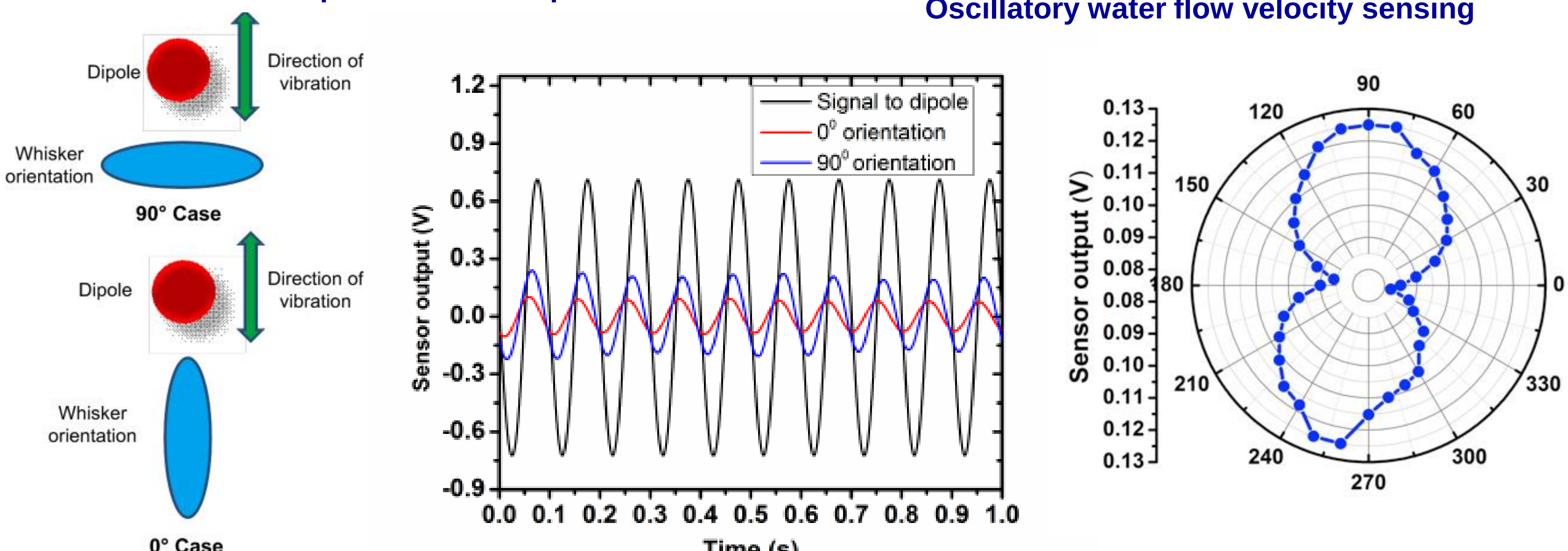
Whisker inspired sensor flow characterization



Schematic of the experimental set-up



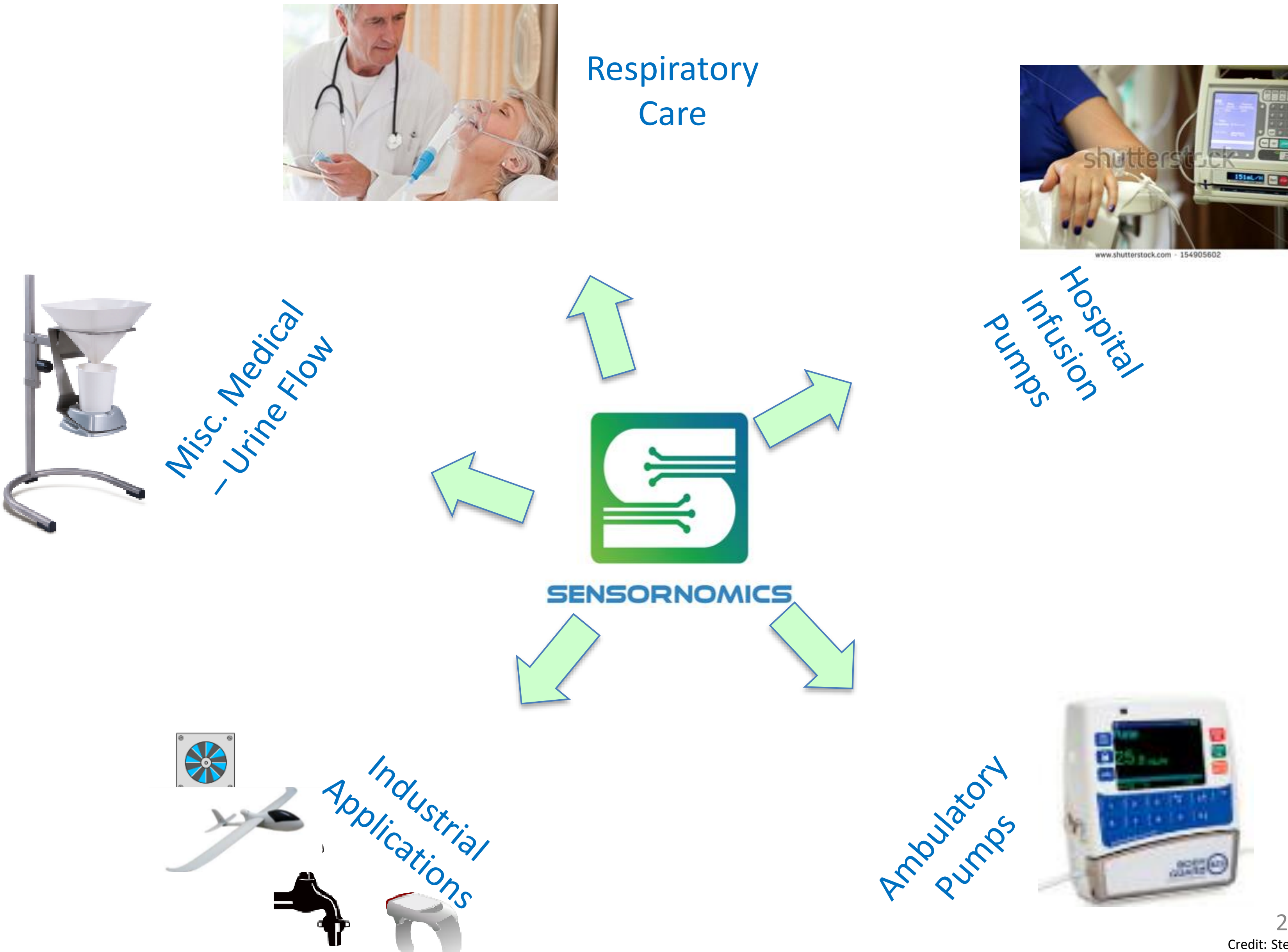
Oscillatory water flow velocity sensing



Directional dependence of the MEMS whisker sensor output due to its elliptical cross-section

Journey from lab-to-market

Market Size & Adjacencies: Lucrative Options Abound



Credit: Steve Blank

Infusion Pump: A Blessing With Flaws (Sometimes Fatal)

What If We Can Read The Live Infusion Rates?

A New Standard of Care?

Funding, Team and Roadmap

2014

SMART Innovation Centre
inspired by the Deshpande Center at MIT
Singapore-MIT Alliance for Research and Technology

Fund of 450,000 S$
≈ 300,000 Euros

Biomimetic microsensors for flow monitoring in Intravenous infusions, urine drainage and sleep apnea applications

2014-16

Dr. Shen Zhiyuan
(Postdoc)

Mr Vignesh
(Research Engineer)

Dr Mohsen
(Post Doc)

Mr Irwin
(Business consultant)

Team formation
Supervision

2016

SENSORNOMICS

Start-up

Creating New Standards of Care with the Future of Flow Sensing

Thank you for your patient listening…..