Dome shaped array of pressure sensors for underwater flow sensing and object detection

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**DOME SHAPED ARRAY OF PRESSURE SENSORS FOR
UNDERWATER FLOW SENSING AND OBJECT
DETECTION**

**KANHERE ELGAR VIKRAM
SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING
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DOME SHAPED ARRAY OF PRESSURE SENSORS FOR UNDERWATER FLOW SENSING AND OBJECT DETECTION

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Abstract

Autonomous underwater vehicles (AUVs) play a critical role in underwater surveys and explorations, which are beneficial to commercial sectors like oil and gas industry and scientific research disciplines like oceanography. AUVs rely on acoustic and optical sensing systems to be aware about their surroundings. However, the applicability of these conventional sensing systems is hindered in dark and turbid waters. Passive mechanoreception provides an alternative approach to overcome the limitations of conventional sensing systems, which assists in gathering information about surroundings by discerning flows and disturbances in the vicinity of AUVs. This work is an attempt to develop a passive mechanoreceptive system by drawing inspiration from the mechanosensory expertise of crocodiles.

Crocodiles possess dome shaped pressure receptors called integumentary sensory organs (ISOs) on their skin, which assist them in flow sensing and in locating the origins of disturbances created by movements of other animals. The surface of each ISO is equipped with mechanoreceptors and free nerve endings, which together carry out the task of receiving mechanical stimulus. The mechanoreceptors associated with ISOs are of two types – slowly adapting (SA) which sense steady pressures and rapidly adapting (RA) which sense oscillating pressures. The bio-inspiration drawn from ISOs involves three aspects – dome shape, array of mechanoreceptors on its surface and types of mechanoreceptors.

Inspired by SA and RA receptors of ISOs, two types of dome structures are constructed – SA dome, equipped with piezoresistive sensors to sense steady pressures and RA dome, embedded

with piezoelectric sensors to sense oscillating pressures. With the proposed SA dome, direction and magnitude of steady flows can be perceived in three dimensions by analyzing the output pattern of sensors mounted on the dome surface. The SA dome manifests the ability to detect movement of an object in its vicinity and to determine parameters such as speed, distance and direction of the movement. The proposed RA dome can be employed to detect the position of the source of oscillatory disturbances. The applicability of SA domes in real time applications is demonstrated through sea trial experiments using a kayak equipped with one.

It is critical to conceive a method to construct a dome with large number of sensors positioned at precise locations on its surface. This is achieved by combining MEMS fabrication technology and rapid prototyping technology with a novel strategy of contractively wrapping a hemispherical surface by patterned polymer petals. A dome of radius 1 cm, with a dense array of 17 piezoresistive sensors on its surface, is constructed. This dome can be used for flow sensing, direction detection and profiling flows over a hemispherical surface.

This project demonstrates that ISO-inspired dome shaped pressure sensors can be employed as a comprehensive passive mechanoreception system for AUVs. To the best of our knowledge, this is the first attempt to develop a mechanoreception system by drawing inspiration from ISOs. It is expected that the work undertaken in this project would be a prelude to many more ventures, which will develop sensing systems to mimic the multi-sensory abilities of ISOs on crocodiles in order to enhance sensing capabilities of AUVs.

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Table of Contents

Abstract.....	iii
Acknowledgement	v
Table of Contents	vii
List of Tables	xi
List of Figures.....	xii
1 INTRODUCTION.....	1
1.1 Background	2
1.1.1 Autonomous underwater vehicles	2
1.1.2 Sensing in autonomous underwater vehicles.....	4
1.1.3 Bio-inspiration for underwater sensing	6
1.1.4 Crocodile as bio-inspiration.....	7
1.2 Motivation	8
1.3 Objectives of the project	10
1.4 Scope and organization of the thesis	11
References	12
2 LITERATURE REVIEW	17
2.1 Introduction	18
2.2 Bio-inspiration and biomimetics	18
2.2.1 Underwater sensing: Active and Passive.....	21
2.3 Integumentary sensory organs of crocodiles	23
2.3.1 Distribution of ISOs.....	24
2.3.2 Morphology and ultrastructure of ISOs.....	25
2.3.3 Functions of ISOs	27
2.3.4 Types of mechanoreceptors in ISOs.....	29

2.3.5 Mechanical filtering mechanism	30
2.3.6 Sensitivity of ISOs	31
2.4 Bio-inspiration from ISOs	32
2.4.1 Dome structure	33
2.4.2 Array of mechanoreceptors on dome surface	33
2.4.3 Specialized receptors	34
2.5 A few lessons from lateral line-inspired sensing systems	35
2.5.1 Neuromast-inspired sensors	36
2.5.2 Mechanical filtering mechanism of canal structure	37
2.5.3 Using array of sensors for flow sensing	38
2.5.4 Using array of sensors for object detection	39
2.5.5 Employing intelligent processing algorithms	40
2.5.6 Takeaways from past research on lateral-line inspired sensing system	43
2.6 Conclusions	44
References	45
3 BIO-INSPIRATION AND PROOF OF CONCEPT	54
3.1 Introduction	55
3.2 Bio-inspiration	55
3.3 Design and Fabrication of artificial SA and RA domes	57
3.4 Proof of concept experiments	60
3.4.1 Direction detection using SA dome	60
3.4.2 Direction detection using RA dome	61
3.5 Experimental results and discussions	64
3.5.1 Direction detection using SA dome	64
3.5.2 Direction detection using RA dome	76
3.6 Sea trials	83
3.6.1 Preparation and experiments	84
3.6.2 Experimental results	86
3.7 Conclusions	89
References	90

4 OBJECT DETECTION EXPERIMENTS	93
4.1 Introduction	94
4.2 Object detection and hydrodynamic passive sensing	94
4.3 Object detection experiments	95
4.3.1 Parameters under consideration	96
4.3.2 Fabrication and packaging of SA dome	99
4.3.3 Circuits for improved data acquisition	100
4.3.4 Experimental set-up	103
4.4 Results and discussions	105
4.4.1 Set 1 - Inline movement	105
4.4.1.1 Directionality of the dome based on magnitude of outputs	106
4.4.1.2 Directionality of the dome based on patterns in outputs	107
4.4.1.3 Variation in output with distance and towing speed	108
4.4.2 Set 2 - Variation with lateral distance	110
4.4.2.1 Observations about dip in output	111
4.4.3 Set 3 - Passing by dome	113
4.4.3.1 Directionality of the dome based on magnitude of outputs	114
4.4.3.2 Directionality of the dome based on time lag between first peaks	118
4.4.3.3 Directionality of the dome based on pattern of dips	119
4.5 Conclusions	122
References	125
 5 DESIGN AND FABRICATION OF DOME WITH HEMISPHERICAL ARRAY	 128
5.1 Introduction	129
5.2 Contractive wrapping and design of polymer petals	131
5.2.1. Wrapping a sphere with petals	131
5.2.2 Design of the petals	133
5.3 Fabrication and assembly of hemispherical arrays	135
5.3.1 Design of the devices and masks	135
5.3.2 LCP as a substrate	138
5.3.3 Fabrication of polymer petals	138
5.3.4 Assembly of polymer petals	140

5.4 Characterization of sensors	143
5.5 Flow experiments	146
5.5.1 Flow velocity sensing	148
5.5.2 Flow direction detection	152
5.5.3 Output profile over surface	153
5.5.4 Alternate ways for sensing flow and direction	156
5.6 Conclusions	158
References	159
6 CONCLUSIONS AND FUTURE WORK	164
6.1 Conclusions	165
6.2 Original contributions	166
6.3 Future work	167
6.3.1 Fabrication of RA dome using contractive wrapping	168
6.3.2 Mechanical high pass filtering mechanism	168
6.3.3 Improvements in contractive wrapping method	170
6.3.4 Employing multiple SA and RA domes	172
6.3.5 Employing intelligent algorithms for data interpretation	172
6.3.6 Looking beyond mechanoreception	175
References	176
List of Publications	178

List of Tables

Table 2.1: Notable attempts to fabricate underwater flow sensors which are inspired by sensory organs of aquatic animals.....	42
Table 4.1: Four characteristic patterns for rod moving from south to north on west side of dome.	123

List of Figures

Figure 1.1: A photograph of a commercial AUV – REMUS 100 (Hydroid Inc.), which is a compact light weight AUV [4]	3
Figure 1.2: Main industries and academic fields that benefit from services offered by AUVs.....	4
Figure 1.3: ISOs (black pigmented spots) are scattered on the skin of crocodiles and they assist crocodiles to locate the origin of disturbances in water which in turn helps to locate preys in dark and/or turbid waters [20].	7
Figure 1.4: Schematic illustration: ISO-inspired dome shaped sensor array can serve as a potential system to be stationed on the surface of the AUV, which will facilitate the AUV to construct a highly legible hydrodynamic image of its surroundings. Figures (a), (b) and (c) together depict the ISOs on crocodiles and figures (d), (e) and (f) together represent the dome shaped sensors on AUVs.....	10
Figure 2.1: Overview of biomimetics associated with different science and technology fields. Different objects in nature and their selected properties/functions are listed below associated field. (based on a figure from [10]).	20
Figure 2.2: Crocodilian cranial regions viewed under the scanning electron microscope. (a) The colorized head of an Alligator mississippiensis hatchling. The ISOs (yellow) are visible as circular, dome-shaped elevations. (b) A single ISO is shown at higher magnification, with the elevated central region of the ISO [25].	24
Figure 2.3: The distribution of ISO on body of crocodiles; where presence of ISOs is indicated by the shaded regions [25].	25
Figure 2.4: A schematic representation of the structure of an ISO from a paper by Leitch and Catania (2012) [25]. Discoid mechanoreceptors and free nerve receptors are shown to be situated just below Stratum Corneum (StC) and Stratum Lucidum (StL) layers of the epidermis	26
Figure 2.5: Another schematic representation of the structure of an ISO showing how receptors are lined up under the skin of the ‘touch papilla’ – the term used for ISOs in the paper [30].	26
Figure 2.6: Response of RA and SA receptors to different types of stimuli [25].	30

Figure 2.7: A drawing showing longitudinal and transvers sections of a Pacinian corpuscles with its structural components labeled [40].	31
Figure 2.8: Receptive fields on a forelimb of a crocodile. The numbers represent the sensitivity of the receptor, expressed in terms of indentation threshold (in mN) [25].	32
Figure 2.9: Lateral line system: (a) A photograph of the blind cave fish <i>Astyanax fasciatus</i> with its lateral line marked with a dotted red line. (b) Schematic of superficial neuromasts which are present on the skin surface and (c) Schematic of canal neuromasts which are present within a canal, beneath the skin. Both types of neuromasts have cupula covering sensory hair cells.	36
Figure 2.10: A scanning electron micrograph of a biomimetic neuromast which is made up of a polymer hair standing on a cantilever beam [56].	37
Figure 2.11: Bio-inspired canal structure: (a) Schematic of a bio-inspired artificial canal structure that functions as a mechanical filter [57]. (b) Photograph of a flexible canal with pores, made up of PDMS [57].	38
Figure 2.12: Schematic of an underwater robot with an array of 5 sensors (S1-S5) on its front end. This configuration of sensors was utilized for flow sensing and improving maneuvering of an underwater robot [58].	39
Figure 2.13: Schematic of experimental setup: (a) Four pressure sensors (1 to 4) housed like lateral line array and a cylinder of diameter d is towed parallel to the linear array. (b) Close-up of pressure ports [59].	40
Figure 2.14: An optical micrograph of an artificial lateral line array comprised of 16 hot wire anemometer sensors [52].	41
Figure 3.1: (a) Schematic of the structure of an individual ISO showing discoid and free nerve mechanoreceptors under the skin of dome (based on schematics presented in [1] and [2]). (b) Schematic representation of the proposed dome shaped sensor in which the pressure sensors placed on the surface of the dome would play the role of mechanoreceptors.	56
Figure 3.2: Bio-inspired MEMS RA and SA domes: (a) Piezoresistive LCP membrane pressure sensor with gold piezoresistor on LCP membrane (b) micro-diaphragm piezoelectric pressure sensor with top circular and ring electrodes (c) SA dome constructed using LCP pressure sensors (d) RA dome constructed using PZT pressure sensors.	59

- Figure 3.3: Experimental setup: (a) Schematic of the experimental set up showing the SA dome fixed inside water tunnel (b) Block diagram depicting Wheatstone's bridge circuit with one sensor on SA dome operating as one arm of the circuit and other components in the experimental setup. 61
- Figure 3.4: Experimental setup depicting the position of dipole and dome: (a) Orientation of the dome is changed to position different sensors under the dipole. (b) Block diagram showing all the components in the experimental set up and interconnections. 63
- Figure 3.5: Flow sensing abilities of SA dome: (a) Outputs at five sensors for the case when 'East' sensor is facing the flow in water tunnel. (b) Polar plot for the case when 'East' sensor is facing the flow of speed 0.02 m/s. The iso-contours represent the output values in mV and the output corresponding to 'Center' sensor is denoted by the blue dot within the quadrangle. (c) Averages of the outputs of five sensors with respective standard deviations shown as error bars. 66
- Figure 3.6: Flow over a hemisphere: (a) Flow velocity profile for a flow over 30 mm diameter hemisphere for $Re = 800$ [9] (b) Surface shear flow visualization of flow over hemisphere ($Re = 6.36 \times 10^4$) [10]. 67
- Figure 3.7: Polar plots for the case when 'North' sensor is facing the flow of speeds (a) 0.03 m/s, (b) 0.05 m/s, (c) 0.07 m/s, (d) 0.10 m/s (e) 0.15 m/s and (f) 0.20 m/s. The iso-contours represent the output values in mV and the output corresponding to 'Center' sensor is denoted by the blue dot within the quadrangle. 68
- Figure 3.8: a) Schematic showing side view of hemisphere, direction of approaching flow and red dotted line represents the arc along which C_p values are plotted in 3.8(c). (b) Visualization of flow around a hemisphere and characteristic flow features – 1. Horseshoe vortex system, 2. Stagnation area, 3. Acceleration of the flow, 4. Separation point, 5. Dividing streamline, 6. Shear layer vorticity [11] (c) Pressure distribution over the plane of symmetry (along the red dotted arc in figure 3.8(a)) of the hemisphere in terms of pressure coefficient [12]. 71
- Figure 3.9: Effect of boundary layer on sensing performance: (a) Polar plot for the case when 'South' sensor is facing the flow in the water tunnel. (b) Polar plot for the case when 'South' sensor is facing the flow and dome is placed on a flat surface with leading edge at 10 cm distance from the dome. (c) and (d), bar charts showing average values of output

- of each sensor for ‘dome not on surface’ and ‘dome on surface’ cases respectively for three runs. Error bars represent standard deviation. 75
- Figure 3.10: (a) Output at five sensors when ‘Center’ sensor is below the oscillating dipole at 5 mm distance. (b) Schematic representation of a dipole oscillating at origin and observation point P at angle θ and distance r from origin. In top right corner the direction of oscillation is denoted. (c) Geometry measurements for the case where dipole sphere is at 5 mm distance from the dome..... 76
- Figure 3.11: Direction detection by RA dome: (a) when ‘East’ is facing the dipole (b) when ‘West’ is facing the dipole (c) when ‘North’ is facing the dipole and (d) when ‘South’ is facing the dipole. In each case the distance between the dipole and the dome is 5 mm. The iso-contours represent output voltage (in mV) and the output for ‘Center’ sensor is represented by the blue dot within each quadrangle..... 78
- Figure 3.12: (a) Plot showing variation in output at five sensors with change in distance between dome and dipole when ‘East’ is beneath the dipole (b) Nonlinear fit to the output of ‘East’ sensor..... 79
- Figure 3.13: Simulation for RA dome: (a) Geometry used in the simulation: A dome of radius 10 mm is placed beneath an oscillating sphere of radius 7.6 mm. (b) The pressure field generated due to the sphere oscillating at 30 Hz. (c) Polar plot of simulation results for ‘East’ beneath the dipole at 5 mm distance. (d) Variation in the pressure values at devices ‘East’, ‘Center’, ‘West’ and ‘North’ with the distance between dipole and dome. 81
- Figure 3.14: (a) Photograph of piezoresistive, LCP pressure sensor (b) Image of 3D printed dome with sockets for placement of the LCP pressure sensors. (c) An SA dome with LCP piezoresistive pressure sensors mounted on it. (d) An SA dome mounted on the sidewall of the front end of kayak. ‘East’ sensor faces the front end whereas ‘West’ sensor faces the rear end of the kayak..... 85
- Figure 3.15: Diagram depicting the control scheme employed during sea trials: A computer is used to autonomously control the movements of kayak and another computer is used to record the data from an on-board computer..... 86
- Figure 3.16: Outputs of sensors ‘East’, ‘West’, ‘North’ and ‘South’ when kayak is held in the stream and then is released to drift along with the flow. ‘East’ sensor being the one facing the flow shows the maximum reduction in the output..... 87
-

Figure 3.17: Polar plots depicting the outputs of the sensors when kayak moves upstream and downstream.	88
Figure 4.1: A schematic showing the top view of the rod and dome to depict the directions and axes system.	97
Figure 4.2: (a) Photograph of the pressure sensor with gold piezoresistor patterned on a liquid crystal polymer membrane. (b) Image of an SA dome constructed by mounting five piezoresistive pressure sensors on a 3D printed dome. The contacts of the sensors are connected to shielded wires passing through the dome.	100
Figure 4.3: Building blocks of the data acquisition system used for object detection experiments	100
Figure 4.4: Circuit diagrams: (a) Wheatstone's bridge circuit and (b) filter and amplifier circuit. For simplicity of diagram, first order RC filter is shown. However a third order RC filter is used in experiment with R and C values as mentioned in the diagram.....	102
Figure 4.5: A photograph of printed circuit board containing five Wheatstone's bridge and five filter- amplifier circuits.	103
Figure 4.6: (a) SA dome placed on a support slab inside a towing tank. A rod attached to a gantry can be towed at desired speeds and directions.....	104
Figure 4.7: Schematic representation movements in each of the sets of experiments: (a) Set 1 with inline movement (b) Set 2 with variation in lateral distance (c) Set 3 where rod is passed by the dome. In each case the black arrow denotes the path of the movement of rod and the red arrow denotes the distance parameter.	105
Figure 4.8: Top view of the experimental set-up in Set 1, with 'North' (N) and 'South' (S) sensors labeled. The yellow arrow denotes the line along which a rod is towed and it is stopped at a distance denoted by the red arrow. The movements executed in this set are towards 'South' and 'North' sensors.	106
Figure 4.9: Directionality of SA dome: Polar plots depicting the outputs of the sensors when rod moves towards (a) North and (b) South sensors at a speed of 0.2 m/s and stops at a distance of 2 cm. The values denoted in the plots are averages taken over five runs.....	107
Figure 4.10: Outputs of (a) 'North' and (b) 'South' sensor, when the rod movement occurs on north side at a speed of 0.6 m/s and stops at a distance of 2 cm.	108

Figure 4.11: (a) Variation in output of ‘North’ sensor with distance, for the cases when the rod is moved on north side at speed 0.1 m/s. (b) Variation in output of ‘North’ sensor with towing speed, for the cases when the movement occurs on north side at a distance of 6 cm. In both the plots means of five runs are presented and standard deviation is represented by the error bars.....	109
Figure 4.12: Top view of the experimental set-up in Set 2. The movements executed are in straight line denoted by solid yellow arrows at a lateral distance denoted by red arrow.	110
Figure 4.13: Output of ‘East’ sensor for rod moved at speed 0.2 m/s towards ‘South’ sensor at lateral distances (denoted by red arrows) of 1, 2, 4 and 6 cm. The dip in output of ‘East’ for lateral distance of 6 cm, is marked with red dotted ellipse.	112
Figure 4.14: Top view of the experimental set-up in Set 3. The movement of the rod is along the solid yellow arrow which is at a distance, denoted by red arrow, from the dome.....	114
Figure 4.15: Outputs of four sensors – ‘East’, ‘West’, ‘North’ and ‘South’ when the rod is towed from south to north, passing by the dome at a distance of 6 cm and at a speed of 0.2 m/s.	115
Figure 4.16: Polar plots showing magnitudes of outputs of four sensors – ‘East’, ‘West’, ‘North’ and ‘South’ when the rod is towed from south to north at a distance of 6 cm and at a speed of 0.2 m/s. (a) Output values of the peaks immediately after the rod passes by the dome at 13 s mark. (b) Output values after 20 s mark. All the values in the polar plots are averages taken over 5 runs.	116
Figure 4.17: (a) Variation in output of ‘South’ sensor with towing speed, when the rod passes by the dome a distance of 6 cm. (b) Variation in output of ‘West’ sensor with distance, for the cases when the rod passes by at distances at speed 0.2 m/s. In both the plots means of five runs are presented and standard deviation is represented by the error bars.....	118
Figure 4.18: Schematic representation of top view of the dome and rod system with its measurements.....	119
Figure 4.19: The dips in the outputs of the sensors: For north to south movement, ‘East’ and ‘South’ show dips and for south to north movement, ‘East’ and ‘North’ show dips.	121
Figure 4.20: Schematic representation of movement of rod from south to north on the west side of dome.	122

- Figure 5.1: k-petal wrappings for a sphere; k is the number of petals: (a) 3-petal wrapping and (b) 4-petal wrapping [17]..... 132
- Figure 5.2: Petal wrappings for hemispherical dome. 4-petal case: (a) 4-petal wrappings for a dome with one of the petals highlighted in blue, (b) dimensions of a petal in 4-petal case, and (c) a half petal in 4-petal case showing the parameters b and c. 8-petal case: (d) 8-petal wrappings for a dome with one of the petals highlighted in blue, (e) dimensions of a petal in 8-petal case, and (f) a half petal in 8-petal case showing the parameters b and c. 134
- Figure 5.3: Simulations for determining the positioning of piezoresistor: (a) Geometry of the diaphragm used in the COMSOL simulation. (b) A 3D profile showing the total displacement of the diaphragm under a boundary load of 10 N/m^2 . (c) A line plot depicting xx component of the stress tensor along diameter of the diaphragm. (d) Pattern of the piezoresistor designed by taking the polarity of the stress into consideration. 136
- Figure 5.4: Schematics of mask: (a) The design of a 4-inch wafer mask for fabricating petals. (b) A single petal with two piezoresistor patterns on it. (c) A close up of the schematic of zig zag pattern of the piezoresistors. (d) The dimensions of the zig-zag pattern of a gold piezoresistor. 137
- Figure 5.5: Fabrication process: (a) Bare LCP after removing the copper cladding from both sides; (b) Spin-coating photoresist on LCP; (c) Patterning the photoresist by photolithography; (d) Sputtering Cr/Au layer on the patterned photoresist; (e) Removal of unwanted Cr/Au layer and the photoresist in Lift-off process..... 139
- Figure 5.6: Photographs of patterned polymer petals: (a) A 4-inch wafer size LCP, patterned with gold piezoresistors with twelve polymer petals and four single piezoresistors. (b) A single polymer petal with 2 gold piezoresistors on it with the contact pads of both the resistors provided at the base of the petal. (c) A zig-zag pattern of gold piezoresistor under microscope. 140
- Figure 5.7: Schematics of different components of petal-dome assembly: (a) A petal with two patterned gold piezoresistors (b) A 3D printed support pillar with a cavity at the top (c) Back side of a petal after attaching two support pillars to the petal in such a way that the cavities on the pillars lie exactly beneath the gold piezoresistors (d) Mounting of a petal

on the 3D printed dome. The support pillars fit into the cavities on the dome and the petal conformably attaches to the dome.	141
Figure 5.8: Photograph of domes after petals are mounted on them: (a) a dome with 4 petals (b) a dome with 8 petals (c) 8-petal dome with contact pads on the petals connected to wires using conductive epoxy.....	142
Figure 5.9. Time response of the sensor (a) positive step (b) negative step	144
Figure 5.10. Output of the sensor while facing the flow of speeds ranging from 0.2 to 15 m/s.	145
Figure 5.11. (a) Linear fit for the output of the sensor for speeds 0.2, 0.5, 1.0, 3.0 and 5.0 m/s. (b) Distribution of calculated flow speeds around the true value of flow speed of 5 m/s....	146
Figure 5.12: Nomenclature of the petals and sensors on the dome: The petals are labeled from A to H and the sensors are numbered from 1 to 16 with the sensor at the apex numbered 17. Letter ‘L’ denotes that the position of the sensor on a petal is lower i.e. towards the base of the dome whereas letter ‘U’ indicates that the sensor is at an upper level i.e. towards the apex of the dome.	147
Figure 5.13: Experimental setup: (a) A block diagram depicting various components of the experimental setup and the Wheatstone’s bridge (b) The dome is mounted on a rotatable base and is placed inside a wind tunnel.	148
Figure 5.14: Output of the sensors 4 and 12 when petal F on the dome faces the air flow of speed 5 m/s.....	149
Figure 5.15: Output of the sensors at 3, 4, 11 and 12 when petal F on the dome faces the air flow of speeds 0.2 m/s, 0.5 m/s, 1 m/s, 3 m/s and 5 m/s.	150
Figure 5.16: (a) Schematic of dome with support base showing positions of sensor 11 and sensor 12 (b) Side view of horseshoe vortex formation, upstream of the hemisphere ($Re = 1.4 \times 10^3$) [27].	151
Figure 5.17: Output of the sensors 3, 4 (petal B) and 11, 12 (petal F) when dome is rotated in steps of 45° to bring each petal facing the air flow of speed 5 m/s. The error bars represent the standard deviation in the respective outputs over 3 runs.....	152
Figure 5.18: Output profiles across the dome surface when placed in the airflow of speeds 0.2 m/s, 1 m/s and 5 m/s.	154

Figure 5.19: Time-averaged streamlines on the base and on dome surface, showing horseshoe vortex moving down the streamline along either sides of the hemisphere (top view) [29].	155
Figure 5.20: Spatially digitized output profiles across the dome surface when placed in the airflow of speeds of 0.2, 0.5, 1 and 3 m/s.	157
Figure 6.1: Three strands in which the work undertaken in this project is categorized.	166
Figure 6.2: Schematic of longitudinal and transverse cross sections of Pacinian corpuscles depicting its components and dimensions.....	169
Figure 6.3: A schematic showing polymer chains and self-crosslinked flexible hydrogel structure with crosslinking points (red) and water molecules (blue) entrapped within its network.	170
Figure 6.4: Well-like structure of SU-8, fabricated through MEMS fabrication processes, can replace 3D printed support pillars.....	171
Figure 6.5: Supervised machine learning: Various building blocks and the flow of the process.	174

1

INTRODUCTION

This chapter presents a brief introduction of background of the research topic, including importance of autonomous underwater vehicles (AUVs), need for enhancing their sensing capabilities and how bio-inspiration from crocodiles can play a crucial role in this regard. Besides, the objectives of this project along with the scope and organization of the thesis are elaborated.

1.1 Background

1.1.1 Autonomous underwater vehicles

Autonomous Underwater Vehicles (AUVs) are submersible vehicles which can carry out tasks without any human intervention during a mission. They are underwater robots designed for executing specific assignments. More precisely, they can be described as “robotic devices that are driven through water by a propulsion system, controlled and piloted by an on-board computer, and maneuverable in three dimensions” [1]. AUVs are part of a larger group of submersibles called Unmanned Underwater Vehicles (UUVs). The larger group includes tethered Remotely Operated Vehicles (ROVs) and unmanned untethered vehicles. Vehicles from both these categories are connected to a remote operator and they are controlled by the operators through communication links. On the contrary, there is no communication link between an AUV and remote operator. An AUV takes care of its own control throughout the mission and returns after completing a pre-defined venture [2]. Though underwater vehicles like submarines and torpedoes came into existence in 19th century, first ‘real’ autonomously controlled submersible was developed in late 1950s at Applied Physics Laboratory in University of Washington. After a few decades of advancements, the first commercially available AUVs arrived after 2000 [1]. Figure 1.1 depicts a new generation commercial AUV – REMUS 100 (Hydroid Inc.) which is used for marine research, defense and hydro-graphic surveys. As human needs and curiosity to explore seas for various purposes will rise, so will be the demand for AUVs. The autonomous underwater vehicle market is forecasted to grow from USD 213 Million in 2016 to USD 498 Million in 2022 [3].

Figure 1.1: A photograph of a commercial AUV – REMUS 100 (Hydroid Inc.), which is a compact light weight AUV [4].

AUVs are used for various applications where there is need to reach out to remote underwater terrains or in conditions which could be dangerous for human life [5]. AUVs provide opportunity to carry out the missions without risking human life. One of the major sectors that exploit the services provided by AUVs is the oil and gas industry. Before building oil platforms and installing pipelines, a thorough mapping of the seabed is necessary. AUVs equipped with various sensing systems consisting of acoustic and optical sensors that can provide a high resolution data of the topography of the seabed [6]. AUVs can also carry out detection and inspection of pipelines on the seabed. They move along the pipeline and collect data regarding the burial and corrosion of the pipelines which are very critical from the point of view of maintenance [7]. The second major sector in which AUVs have a critical role to play is scientific research. Various fields of engineering and sciences like oceanography, geoscience, archaeology and environmental sciences require observations and collection of a variety of data from oceans and water bodies around the globe. For example in geosciences, AUVs can assist in collecting data associated with submarine volcanism, hydrothermal vent studies, mapping of chemosynthetic

ecosystems and mapping of seafloor features [8]. AUVs can contribute to fisheries [9] and marine biology research [10] by assisting in tracking the population of fish and other marine animals. Military is another critical application area where AUVs play a vital role. AUVs are deployed in missions pertaining to surveillance, mine countermeasures, anti-submarine warfare and time-critical strikes [11]. AUVs are also useful for search and rescue operations at sea [12]. Figure 1.2 depicts various industries, sciences and engineering fields which employ AUVs.

Figure 1.2: Main industries and academic fields that benefit from services offered by AUVs.

1.1.2 Sensing in autonomous underwater vehicles

The technology associated with construction and functioning of AUVs can be classified into six ‘technology long poles’, namely i) Autonomy, ii) Energy systems, iii) Navigation, iv) Sensor systems, v) 3D imaging and vi) communications [2]. The focus of this work lies mainly in –

sensor systems. The success of an AUV depends upon its ability of gathering as much information of its surroundings as possible, making decisions based on the data collected and implementing the decision. Traditionally, to collect inputs about its surroundings, AUVs have relied heavily on active sensing strategies. In active strategies, a signal (optical or acoustic) is directed towards target and the reflected signal is analyzed to gain information about the target. As active sensing involves transmission and reception of signal, under certain unfavorable environmental conditions it is unable to provide true or sufficient data. An example of active sensing is Sound Navigation and Ranging (SONAR). Though SONAR technology is widely used, it faces issues like sonar blind zones [13]. In littoral zones, i.e. in shallow waters, the capability of sonar is hindered by issues like multipaths which leads to less credible mapping [14]. In addition, SONAR may not perform well in water having bubble clouds, because the obtained sonar image is ‘cluttered’ due to strong scattering by bubbles [15]. Moreover, the intense sound waves transmitted by sonar sensing systems may cause fatal injuries to aquatic animals [16]. Optical method is another example of an active sensing system. In optical method, light is transmitted and with the help of cameras the surroundings are mapped. But this method may not be effective in turbid water where visibility is hindered [17]. All the active sensing strategies need to emit energy in one form or the other, which means an energy source is their inherent requirement. The energy sources and other equipment like transmitters and receivers add to the weight of AUV, making them less energy efficient. It is critical for an AUV to possess an alternate sensing system that can overcome these issues.

In passive sensing, no signal is transmitted from the AUV to collect information. Therefore, the sensing mechanism doesn’t need a heavy energy source, making it a more efficient method. It also enables AUVs to collect information without disturbing the surrounding environment and

other living beings in the vicinity. One of the most effective underwater passive sensing strategies is passive hydrodynamic sensing which relies on drawing information from the hydrodynamic signals generated by moving objects and flows. Moreover, information about flows and other hydrodynamic phenomena like vortices can be used to advantage for energy efficient maneuvering. For AUVs, passive hydrodynamic sensing can be the alternative that provides necessary information about its surroundings in cluttered, shallow or turbid waters.

1.1.3 Bio-inspiration for underwater sensing

In nature, animals have evolved different sensing strategies to survive in the struggle of life. Animals need better sensing abilities for various reasons - to search and locate prey or food, to detect predators before being caught, and to find partners for reproduction. Considering these reasons, it won't be farfetched to say that the sensing abilities of animals play a paramount role in the survival of a species. Many aquatic animals, through the evolution process have developed very peculiar passive sensory organs. For example, the blind cave fishes use sensory organs called lateral line to sense the flow of the stream [18]. Sharks, freshwater teleosts such as catfish, and salamanders have specialized electroreceptors for passive electro-location by sensing the electric fields generated by other organisms [19]. Crocodiles perform passive sensing through mechanoreceptors called Integumentary Sensory Organs (ISO) or Dome Pressure Receptors (DPRs) [20]. The sensing strategies and organs that these animals employ are energy efficient, sensitive and capable of sensing in conditions in which human-made sensors may not be able to operate successfully. The sensing systems of these animals are testimony to the fact that nature is a master of sensing technologies and we can take a leaf or two out of its book.

1.1.4 Crocodile as bio-inspiration

Crocodiles have gone through 85 million years of evolution and they are one of the most dominant species when it comes to land-water interfaces [21]. They have proved to be a successful species partly due to their highly evolved sensory organs like ISOs which are scattered on the skin of crocodiles (as shown in Figure 1.3), assisting them to locate the origin of disturbance, both on water surface and inside water, enabling them to hunt preys even in dark environment and turbid waters [20, 22].

Figure 1.3: ISOs (black pigmented spots) are scattered on the skin of crocodiles and they assist crocodiles to locate the origin of disturbances in water which in turn helps to locate preys in dark and/or turbid waters [20].

Researchers have been trying to explore the structure and functions of ISOs, since the second half of the 20th century. Monica Von Doring, in 1973 studied the ultrastructure of lamellated mechanoreceptors in the skin of reptiles - caiman to be precise - which is a genus in order Crocodilia [23]. Jackson et al., in 1996 studied the physiology along with the ultrastructure of ISOs [24]. But the function of ISOs was not confirmed until 2002, when Soares D performed experiments to get enough evidence to suggest that the dome shaped pressure receptors help

crocodiles in sensing ripples in water [20]. In 2012, Leitch and Catania gave a detailed account of distribution of ISOs over the body of crocodiles, structure of ISOs, innervation of the afferents from ISOs, and sensitivity and response of the neurons in ISOs to mechanical stimulus [22]. ISOs are dome shaped sensors with number of mechanoreceptors lined just beneath the epidermis. The mechanoreceptors receive mechanical or hydrodynamic stimuli. Mechanoreceptors associated with ISOs are of two types – rapidly adapting (RA) and slowly adapting (SA). Rapidly adapting receptors are responsible for sensing oscillating mechanical signals generated by movements of other animals. Slowly adapting receptors are responsible for sensing steady mechanical signals which are caused by flows. This implies that ISOs form a comprehensive sensing system with ability to perceive signals generated by other moving animals as well as steady flows. ISOs have the potential to be an inspiration for underwater passive sensors and it is worth an attempt to develop a sensory device or system based on ISOs on crocodiles. Devices inspired by the ISOs on crocodiles can be a valuable addition to the sensory abilities of AUVs. It is a fascinating venture to first understand the various aspects of mechanoreception in ISOs and then explore the possibilities of developing a passive mechanoreception system for AUVs.

1.2 Motivation

The motivation behind this work is to explore solutions regarding the issues faced by AUVs in the sensing domain, in the form of a passive hydrodynamic sensing system inspired from ISOs on crocodile. As mentioned earlier, in cluttered and turbid waters, SONAR and visual sensing capabilities of AUVs are impaired. Under these conditions, passive hydrodynamic sensing systems could be an alternative which can enable AUVs in discerning the flows and other

hydrodynamic phenomena around them. The information about flows and vortices around AUVs could be used for energy efficient maneuvering.

In past, bio-inspirations drawn from lateral line of fish and harbor seal whiskers have been instrumental in development of hydrodynamic passive sensors and systems [25, 26]. The basic sensing units in these sensing systems are flow sensors with standing pillar structure. The pillar structure bends owing to the drag force due to flow. The bending of the pillar can provide information of flow in two dimensions that are perpendicular to the pillar height. On the other hand, a crocodile-inspired dome would have pressure sensors scattered on its surface. In other words, the dome possesses an array of pressure sensors on a hemispherical surface. Each pressure sensor can receive the stimulus of force exerted by the flow and therefore the dome as a whole is capable of receiving and discerning the stimulus in three dimensions. As far as the stimulus is concerned, for both the systems it is the drag force that the flow imparts on the respective device components. For lateral line inspired sensors, the stimulus is the drag force that acts on the standing pillar whereas for the sensors on an ISO-inspired dome, the stimulus is the drag force component that is perpendicular to diaphragm of the pressure sensor.

Figure 1.4 depicts an illustration of how an AUV can be equipped with dome shaped sensors inspired by ISOs on crocodiles. Figures 1.4(a), (b) and (c) show the ISOs on the skin of crocodiles and Figures 1.4(d), (e) and (f) depict a schematic of an AUV with ISO-inspired domes placed on its surface. The domes mounted on the surface of the AUV, are similar to ISOs distributed on the skin of crocodiles. As shown in Figure 1.4(f), the surface of an ISO-inspired dome would be embedded with number of pressure sensing units which will sense the mechanical stimulus. Another important aspect of ISOs is that there are two types of receptors – SA and RA, to receive mechanical stimuli of different types. This feature makes it a

comprehensive mechanoreception system. It is a highly desired feature for a sensing system, warranting it to possess receptors with specialized sensing abilities. An ISO-inspired mechanoreception system, will have two types of domes – SA dome sensing steady or constant pressures and RA dome sensing oscillating pressures.

	Distribution of domes		Individual dome
ISOs on crocodiles	(a)	(b)	(c)
ISO-inspired artificial dome shaped sensors on AUV	(d)	(e)	(f)

Figure 1.4: Schematic illustration: ISO-inspired dome shaped sensor array can serve as a potential system to be stationed on the surface of the AUV, which will facilitate the AUV to construct a highly legible hydrodynamic image of its surroundings. Figures (a), (b) and (c) together depict the ISOs on crocodiles and figures (d), (e) and (f) together represent the dome shaped sensors on AUVs.

1.3 Objectives of the project

The overall goal of this project is to develop a passive hydrodynamic sensing system drawing inspiration from ISOs on crocodiles. This project is divided into the following objectives:

1. To get inspiration from actual understanding of morphology, structure, receptor types and functions of ISOs on crocodiles.

2. To design and fabricate dome shaped pressure sensors based on the structure and two receptor types of ISOs, employing piezoresistive and piezoelectric pressure sensors.
3. To explore the direction detection and flow sensing abilities of the two types of the dome shaped sensors.
4. To investigate the object detection abilities of the artificial dome shaped pressure sensors.
5. To propose and implement a new approach for fabrication of a dome with inbuilt pressure sensing elements on its surface.

1.4 Scope and organization of the thesis

The thesis is arranged in six chapters. Chapter 1 presents a brief introduction of the background of the research topic. It describes the importance of autonomous underwater vehicles and the issues with their sensing capabilities. Further, it briefly introduces biological sensors and then goes on to mention how ISO on crocodiles could provide cues for development of a passive mechano-reception sensing system.

Chapter 2 firstly discusses the scope and advantages of bio-inspiration and the biomimetic approach and provides examples of bio-inspired sensors pertaining to underwater active and passive sensing. Then it provides a comprehensive literature review about ISOs on crocodiles. The detailed survey includes distribution, morphology, ultrastructure and functions of ISOs, types of mechano-receptors associated with them and their innervation.

Chapter 3 starts with fabrication of slowly adapting and rapidly adapting domes by employing piezoresistive and piezoelectric pressure sensors, respectively. Then it describes the proof of concept experiments in wind and water tunnels, followed by experiments with domes mounted

on kayaks. These experiments provide evidence to the fact that ISO-inspired dome shaped sensors can be utilized for passive hydrodynamic sensing.

Chapter 4 details out the experiments conducted to explore the object detection abilities of slowly adapting dome. The objective of the experiments is to study how the patterns of outputs of sensors on the dome vary with parameters like distance of the object from the dome, speed of movement of the object and the direction of the movement.

Chapter 5 provides a detailed account of implementing the contractive wrapping approach to fabricate a hemispherical array. The chapter elaborates on the aspects of contractive wrapping, design of petals and assembly of patterned petals to form a hemispherical array. It then goes on to describe the experiments conducted to investigate the flow sensing and direction detection abilities of the dome.

Chapter 6 provides a summary of main contributions of this work and then describes different prospective research directions that can stem from it.

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2

LITERATURE REVIEW

This chapter briefly describes the scope of the field of bio-inspiration and biomimetics. It then proceeds to comprehensively discuss the morphology, structure, innervation, types and functions of integumentary sensor organ (ISO) of crocodiles. It also sheds light on past bio-inspired attempts to enhance the sensing capabilities of AUVs, especially in hydrodynamic sensing and discusses them with reference to prospective ISOs-inspired sensing system.

2.1 Introduction

The goal of this project is to improve the sensing capabilities of autonomous underwater vehicles. The human made machines started diving and staying underwater for prolonged time only from 19th century. However, humans are not the first ones to visit the waters. There are aquatic animals that have been residing there for millions of years and have developed unique sensory organs and strategies. The sensing strategies and capabilities are absolutely vital for animals because they may prove to be the difference between escaping from a predator and getting caught by a predator, or between capturing a prey and starving. Therefore these animals are compelled to constantly improve them through evolution. Considering this, the quest for an innovative sensing system for AUVs can start with exploration of how nature has resolved the sensing issues. How various aquatic animals that inhabit underwater environments take care of the sensing requirements? Which animals have inspired human-made underwater sensing systems in past? In general, how bio-inspired or biomimetic approach adds value to human-made systems? Answers to these questions are presented in the following sections.

2.2 Bio-inspiration and biomimetics

Bio-inspiration and biomimetics, at its heart is a philosophy of finding solutions to engineering or scientific problems by observing the way nature has resolved a similar problem and then trying to imitate the method. One may wonder, what is so special about solutions provided by nature. The solutions by nature, as we see today are indeed peculiar for the fact that they aren't the solutions that are momentary or short lived. They are the end products (as of today) that have come into existence through a constant process of quality check and revamp over millions of years of evolution. This process ensures that the characteristics of systems which are not

beneficial are discarded and the ones which are advantageous are retained and further upgraded. One of the most important underlying principles for any system in nature is that it is energy-efficient and sustainable. Therefore an apt definition of biomimicry is that “it is an approach to innovation that seeks sustainable solutions to human challenges by emulating nature’s time tested patterns and strategies” [1]. Bio-inspiration and biomimicry can affect every walk of life and every aspect of human creation, such as energy generation [2], transportation [3], communication/networking [4], materials science [5], medicine [6, 7], architecture [8] and computation [9]. Many disciplines of engineering are being positively influenced by bio-inspiration. The scope and depth of the bio-inspired and bio-mimicking approach is elaborated in several review papers [10-13]. Figure 2.1 provides a glimpse of how different organisms like bacteria, animals on land, water, air and even inanimate objects like seashells and bones can provide insights into solving various problems from different disciplines [10]. For example, in figure 2.1, one of the properties listed for plants is self-cleaning which can be observed clearly in lotus leaf. Inspired from the surface of lotus leaf, researchers have fabricated self-cleaning surfaces which can have applications in textile and glass industry [14]. The list of organisms/objects provided in figure 2.1 is not at all exhaustive, but it shows how nature is full of wonderful structures, materials, strategies and systems which can help us improve our life in a more sustainable and nature friendly way.

Figure 2.1: Overview of biomimetics associated with different science and technology fields. Different objects in nature and their selected properties/functions are listed below associated field. (based on a figure from [10]).

As this work is primarily focused on underwater sensing systems, the review is restricted to bio-inspired attempts to build underwater sensing systems. The subsequent sections will

progressively narrow down the focus from underwater sensing to underwater passive hydrodynamic sensing.

2.2.1 Underwater sensing: Active and Passive

For survival, animals need to collect information about their surroundings. The information is collected by receiving energy in a certain form – mechanical, chemical, heat, light or acoustic. The sensing strategies could be broadly classified into two categories based on the source of energy. Sensing in which energy is generated by the animal itself, is known as active sensing, whereas if the source of energy is external, then the sensing is called passive sensing. If we restrict to underwater examples, the sonar technique employed by dolphins to sense obstacles and preys, is an active sensing strategy. Dolphins send out energy in form of an acoustic signal and gather information from the signal reflected from the target [15]. On the other hand, certain fishes can sense mechanical disturbances created by other swimming animals [16] and this is an example of passive sensing. Each of the strategies is suitable for that particular animal and environment. Through the evolutionary process, nature keeps upgrading its ‘sensing technology’. Human-made sensors have achieved great progress but many of the sensing mechanisms and organs in nature are still superior in terms of sensitivity, selectivity or reaction time and they can provide ideas to improve human-made sensing systems. There are several instances of such bio-inspired improvements, associated with both active and passive sensing.

In active sensing, inspiration from sonar of dolphins is a very interesting example. Dolphins’ sonar can detect objects surrounded by cloud of bubbles [17]. However, human-made sonar is yet to achieve this feat. Such a superior performance of the dolphin sonar could be attributed to certain factors like, their mobility and signal processing abilities that their brains may have acquired over the evolutionary process. As far as signal processing is concerned, it is tough to get

a direct evidence of how data is processed in a dolphin's brain. But the expertise of dolphins has inspired researchers to speculate different signal processing strategies that are probably employed by dolphins. Even these speculations have contributed to valuable advancement of traditional sonar technology. One classic example of this is a technology called 'biased pulse summation sonar (BiaPSS)' [18]. BiaPSS sends out signals similar to those generated by dolphins and processes reflected signals with a non-linear mathematical technique to discriminate the target from the scattering caused by bubbles. Through experiments, BiaPSS is found to be effective in achieving the objective which otherwise is not possible using standard sonar processing.

Another active sensing strategy that could be of interest to AUVs is electrolocation. This strategy is inspired from weakly electric fishes possessing an electric organ discharge to generate an electric field and an array of electroreceptors on their body to sense perturbations in the field [19]. These fishes are not only able to locate an object, but can also discriminate between different objects based on their electrical properties [20]. Solberg et al. in 2008, presented a bio-inspired active electrolocation system which can successfully locate spheres with an average positional estimation error of about 3% of the diameter of a sphere [21]. In 2015 Bai et al. presented an algorithm to estimate the size, shape, orientation and location of ellipsoidal objects using an active electrosensing system with multiple sensing electrodes [22].

Similarly, there are several fascinating examples of human-made sensors inspired from passive biological sensors. For example, some teleost fishes have the ability to sense an electrical field generated by other organisms and finding their locations through passive electrolocation [19]. This has triggered development of an underwater docking strategy suitable for murky waters or cluttered environments [23]. Another example is that of sharks with a capability to sense even a

drop of blood in a reservoir as large as a swimming pool, by virtue of the olfactory sensing ability to sense chemical stimuli. The design of the shark's olfactory system has inspired the development of a novel chemical sensor for lead detection [24].

For situational awareness, several aquatic animals such as fishes, harbour seals and crocodiles greatly rely on passive mechano-reception. For these animals, it is critical to be thoroughly aware about the flows and other hydrodynamic events like vortices. This information can be utilized for energy efficient maneuvering through water. The source of mechanical stimuli could either be inanimate, like flow of water, or it could originate from the movements of other aquatic animals. A steady flow of water provides a constant pressure stimulus whereas a flow that crosses an obstacle leaves a vortex trail of low frequency. Similarly, a signal due to the body motion of a swimming fish would be different from that caused by the movement of its fins. The passive mechano-sensing systems that these aquatic animals possess are evolved to be sensitive to stimuli that are most relevant to them. ISOs on crocodiles are a great example of how sensing organs evolve to tackle different types of stimuli. Next section is devoted to understanding morphological and neurological aspects of ISOs and bio-inspiration drawn from these aspects.

2.3 Integumentary sensory organs of crocodiles

Integumentary sensory organs are multi-sensory organs present on the skin of crocodiles and assist them in sensing different types of stimuli. Figure 2.2(a) shows ISOs distributed on the skin of head of a crocodile and Figure 2.2(b) depicts close up of an ISO. The term 'Integumentary Sensory Organ' was first used by Brazaitis P in 1987 [25]. Soares D coined a term called 'Dome Pressure Receptors' (DPRs) in 2002 [26]. The term 'DPR' clearly expresses the structure and functional role of the organ; however, term 'ISO' is more commonly used.

ISOs have been a mystery that biologists have attempted to unravel since 1970s. The research associated with ISOs can be classified in four broad categories. The first category of research on ISOs mainly looks at them from taxonomic perspective. The research in second category is focused on understanding the morphology and ultrastructure of ISOs. The third category comprises the research which focused on investigating the different functions that ISOs can perform for crocodiles. And the fourth category includes works related to studying different receptor types and innervation of ISOs. Researches from these categories have progressed more or less in parallel.

Figure 2.2: Crocodilian cranial regions viewed under the scanning electron microscope. (a) The colored head of an *Alligator mississippiensis* hatchling. The ISOs (yellow) are visible as circular, dome-shaped elevations. (b) A single ISO is shown at higher magnification, with the elevated central region of the ISO [25].

2.3.1 Distribution of ISOs

The major part of initial research was associated with taxonomy studies. The distribution of ISOs on a crocodile's body can help in identifying the classification/taxonomy of the crocodile [27]. ISOs are distributed on the skin of cranial region (i.e. the head region) only in case of family Alligatoridae which includes Caiman and Alligator species as shown in Figure 2.3. For crocodiles from families Crocodylidae and Gavialidae, the ISOs are also present on most of the

entire body and not just on the cranial region. The density of ISOs is the maximum close to teeth and near the rostral-most points of upper and lower jaws. The greatest density is found to be around 2 receptors per mm^2 . The density on the head and in post cranial region reduces to about 0.25 receptors per mm^2 [25].

Figure 2.3: The distribution of ISO on body of crocodiles; where presence of ISOs is indicated by the shaded regions [25].

Crocodilian skin is used to make variety of skin-products. The international trade comprises export of over 1.5 million crocodilian skins per year [28]. Though the market is regulated, there exists illegal trade. The application of the taxonomic research is in the cases involving the illegal trade where identification of the species from the skin products is crucial [29].

2.3.2 Morphology and ultrastructure of ISOs

Understanding morphology and ultrastructure of an organ is an important part in decoding its role and functions. There have been several studies on this aspect of ISOs [25, 30, 31]. ISOs are dome shaped structures. The maximum diameter of ISO is about 200 μm and the minimum one is about 100 μm [25]. Below the layers of epidermis of the skin that covers ISOs, variety of mechanoreceptors are positioned. Each ISO contains a highly branched nerve bundles and the nerves are connected to mechanoreceptors. Just below the cells of the stratum lucidum and corneum which are two outermost layers of skin (Figure 2.4), there are discoid receptors which are rounded and expanded structures. Apart from discoid receptors, there are other

mechanoreceptors in form of free nerve terminals. The discoid receptors and the free nerve terminals together execute the task of receiving mechanical stimulus. ISOs have a distinct pigmentation because the connective tissues beneath receptors contain melanocyte. The outer keratinized layers that cover the ISOs are 60% thinner than those which cover the adjacent scaled regions. Figure 2.5 depicts another version of schematic representation of the organ where the dome shape and the receptors aligned beneath the skin are evident [30].

Figure 2.4: A schematic representation of the structure of an ISO from a paper by Leitch and Catania (2012) [25]. Discoid mechanoreceptors and free nerve receptors are shown to be situated just below Stratum Corneum (StC) and Stratum Lucidum (StL) layers of the epidermis.

Figure 2.5: Another schematic representation of the structure of an ISO showing how receptors are lined up under the skin of the ‘touch papilla’ – the term used for ISOs in the paper [30].

The most notable nerve endings of ISOs are associated with dermal Merkel complex which is located just beneath the dome. Merkel cells are sensory cells which transmit signals to somatosensory neurons depending on the form of the mechanical stimulus it receives. Merkel cells are slowly adapting type of receptors. The function and different types of mechanoreceptors are explained in following sections.

2.3.3 Functions of ISOs

From the research of past five decades, it has been established that ISOs perform multiple functions. Initially mechanoreception was considered to be the main and probably the only function of ISOs. In next four decades, researchers explored and proposed that ISOs could be undertaking a few other sensing responsibilities too. In 1984, G. H. Rodda provided evidence of the ability of juvenile crocodiles to detect magnetic field and use it for navigation purpose [32]. The experimental observations suggested that the older juvenile crocodiles released away from home, may be using geomagnetic map information to select a homeward direction. In 1993, it was hypothesized that ISOs could be involved in secretion of oil-like substance since mud doesn't stick to skin of crocodile and it gets flushed easily from the skin [33]. In 2007, Jackson and Brooks concluded from their experiments that ISOs play a role in distinguishing fresh water from hyper-osmotic sea water [34]. It implies that ISOs can detect the salinity level of water when they are exposed to it. In 2013, Di Poi and Milinkovitch concluded that ISOs, apart from being mechanosensors, also carry out function of thermal and pH sensing [35]. They observed that ISOs are responsive to temperature above 43°C and below 15°C. The response to temperature increased proportionally for temperatures above 43°C and below 15°C. This means that ISOs play a role of an alarm system - which is inactive for normal temperature range but

becomes active for temperature higher and lower than certain threshold values. The temperature sensing capability of ISOs could also be useful in nest site selection and hatching eggs [36]. Di Poi and Milinkovitch also observed that ISOs are sensitive to the increase and decrease in pH value. With the advances in research related to functions of ISOs, it is now clear that ISOs are unique multi-sensorial micro-organs with no parallel in sensing systems in vertebrates.

As mentioned earlier, ISOs have been speculated to have a specialized role in detecting mechanical stimuli [31] and mechanoreception is the most studied function of ISOs. Though there have been hypothesis that ISOs assist in mechanoreception since 1970s, an experimental validation came only in 2002. D Soares, through experiments proved that crocodiles do use ISOs for sensing the disturbances on water surface [26]. During these behavioral trials, crocodiles were observed to orient themselves to a single droplet falling on water surface, in dark and without any auditory cue. After a drop fell on the water surface, the crocodiles could orient and snap their jaws exactly at the location where the drop fell. In 2012, Leitch and Catania observed that, despite facing the opposite direction and having their heads above water; crocodiles are capable of rapidly turning and diving underwater towards the location of the fish [25]. ISOs are also present on the limbs of crocodiles. The most sensitive ones (among those on the limbs) are located on the digits of limbs. These observations suggest that ISOs help crocodiles in reading the disturbances not only on the surface of water but also inside the water. The ISOs present near teeth and on the jaws help crocodiles in discriminating the objects that are held in jaws and in guiding or manipulating the captured food [25]. ISOs, owing to their mechanoreception, are also useful in courtship behavior which involves head/neck rubbing, splashing and sub-audible vibrations [36]. In 2015, Grap et al. investigated the response of crocodiles to surface wave stimulus for different frequencies and determined the behavioral thresholds of the response to the

stimulus [37]. They observed that the threshold values of peak to peak wave amplitude decreased with increase in frequency. They also observed that sensitivity of ISOs to water surface waves is similar to that of semi-aquatic insects but is lower than that of surface feeding fish by an order of magnitude or two.

Researchers are yet to gain comprehensive knowledge about all the functions and neurological aspects of ISOs. However, as of now there is sufficient evidence to claim that ISOs can sense stimuli of multiple types, namely, mechanical, thermal and pH value. Amongst the multiple roles of ISOs, their role as mechano-sensor is well understood.

2.3.4 Types of mechanoreceptors in ISOs

There have been several studies about mechanoreceptors associated with ISOs [30, 38, 39] in 1970s. In 2012, Leitch and Catania carried out a comprehensive research work to explore different mechanoreceptors and their innervation [25]. The mechanoreceptors associated with ISOs are of two types - i) Rapidly Adapting (RA) which respond only for onset and offset of the stimulus, ii) Slowly Adapting (SA) which respond throughout the period of presence of the stimulus. RA receptors in crocodiles are made up of Lamellated corpuscles which are similar to Pacinian corpuscles in mammals. Pacinian corpuscles - are rapidly adapting i.e. they send signals when they sense change in contact pressure but not when the contact pressure is constant over a period of time. SA receptors in crocodiles are made up of Merkel cells, which respond to constant level of stimulus rather than the change in the stimulus.

Figure 2.6: Response of RA and SA receptors to different types of stimuli [25].

In figure 2.6, the response of RA and SA receptors to different stimuli is shown. An RA receptor fires on the onset of a square wave (prominent) and on the offset of a square wave (not so prominent). It demonstrates that RA receptors fire whenever there is a transition in the stimulus level – either from low to high or from high to low. RA receptor also fires periodically for a sinusoidal stimulus. SA receptor fires throughout the presence high level of square wave stimulus and doesn't fire for low level. The firing frequency increases as the stimulus level or intensity increases. It means SA receptors would fire when a constant force is applied and they would also indicate the magnitude of the force through the frequency of the firing. An ISO is associated with either RA or SA receptors. In crocodiles, the proportion of RA and SA domes is almost equal, i.e. about 50% each [25]. In this report henceforth, for convenience, the domes associated with RA receptor-like sensors are called RA domes and the ones associated with SA receptor-like sensors are called SA domes.

2.3.5 Mechanical filtering mechanism

A fascinating aspect about mechanoreception by ISOs is associated with RA receptors. RA receptors carry out the reception of oscillating stimulus through Lamelated corpuscles which are similar to Pacinian corpuscles in mammals. These corpuscles are made up of concentric lamellae

with interconnections connecting them and interlamellar fluid separating them from each other. The lamellae enclose the core that contains nerve ending as shown in figure 2.7.

Figure 2.7: A drawing showing longitudinal and transvers sections of a Pacinian corpuscles with its structural components labeled [40].

The structure of Pacinian corpuscle transmits static signals from outside poorly to the nerve ending at the center. However, dynamic signals are transmitted well to the nerve ending. It implies that the lamellar structure of the corpuscle functions as a mechanical high pass filter by not allowing low frequency signals and transmitting high frequency signals [40].

2.3.6 Sensitivity of ISOs

The skin of crocodiles is covered with receptive fields of different size as shown in figure 2.8. The size of ISOs and their density are different on different body areas. On the large receptive fields, ISOs are less densely positioned. The smaller receptive fields that are restricted to a single ISO, are the most sensitive ones, e.g. ISOs on distal parts of digits could sense forces as small as 0.392 mN. Some ISOs on lower jaw could sense forces as small as 0.078 mN [25]. Similarly, tactile responses are elicited by mechanical displacements as small as 3.9 μm - an indentation

threshold lower than found for the human hand. Sensitivity is the maximum for frequency range 10 Hz to 35 Hz and is less for the higher frequencies [25].

Figure 2.8: Receptive fields on a forelimb of a crocodile. The numbers represent the sensitivity of the receptor, expressed in terms of indentation threshold (in mN) [25].

2.4 Bio-inspiration from ISOs

ISOs are multi-sensory organs with ability to sense pressure, temperature and pH value of water. They are unique as far as range of types of stimuli that a sensing organ can sense. An ISO-inspired dome shaped sensor with multi-sensing capabilities would be an ideal addition to AUVs. As each artificial dome sensor would take care of sensing variety of stimuli, it would make AUV sensing system more energy efficient. Moreover, an array of these sensors would be able to provide comprehensive information about the surroundings. But to attempt to fabricate such a sensor, much more knowledge about mechanisms of reception of each stimuli category (mechanical, pH and temperature), the structure and innervation of corresponding receptors, their probable multiplexing and coordination, is needed. So, though desirable, as of now an ISO-

inspired sensor with multiple sensing capacities may not be possible. However, one step can surely be taken in that direction by focusing on mechanoreception of ISOs. There are several features of ISOs associated with mechanoreception, which can be mimicked to form a dome shaped pressure sensor.

2.4.1 Dome structure

The most noticeable feature of ISOs is their dome shape. The skin of crocodiles is covered with the ISO bumps. An AUV could be envisioned to have its surface equipped with an array of hemispherical dome shaped sensors. A hemisphere, owing to rotational symmetry, makes spatial filtering or beamforming easily achievable [41]. When a stimulus reaches a dome, the section facing the direction of arrival of signal would receive it without any attenuation. However the section on the opposite side would encounter the signal in attenuated form. The attenuation would be due to the protruding dome shape. Moreover, the rotational symmetry of the dome brings parity amongst all the directions.

2.4.2 Array of mechanoreceptors on dome surface

Another important feature of ISOs from the perspective of mechanoreception is that each ISO has an array of mechanoreceptors underneath the outer layer of its skin. This would be the second feature to be incorporated in the ISO-inspired dome shaped sensors. The surface of each ISO-inspired dome would be covered by an array of pressure sensors. The dome shape and the array of sensors on the dome surface, together form a hemispherical array of sensors. A hemispherical array has some peculiar advantages over two dimensional arrays i.e. linear or rectangular arrays. The analysis of the signals received by a spherical array can be carried out in spherical harmonics domain which enables use of algorithms that are efficient [41].

2.4.3 Specialized receptors

As discussed in section 2.3.4, there are two types of mechanoreceptors associated with ISOs – RA and SA. The RA receptors are responsible for sensing transitions or variations in the stimulus, whereas the SA ones are responsible for sensing a constant level of stimulus. This feature of having specialized receptors, working on division of labor principle, is worth mimicking in an ISO-inspired sensing system.

In fact, many biological sensing systems are comprised of different receptors specialized in sensing different types of stimulus. For example, there are four different mechanoreceptors found under skin of human hand. Two of them - Meissner's corpuscle and Pacinian corpuscle, are RA and two mechanoreceptors - Merkel cells and Ruffini endings, are SA ones. The information from all four is coded by brain. Firing of all the 4 receptors at the same time produces the sensation of contact with an object. If only Merkel cells and Ruffini endings fire then it produces sensation of steady pressure on the surface of the skin. If only Meissner and Pacinian corpuscles fire then it produces sensation of tingling or vibration [42]. The lateral line in fish is also equipped with two types of receptors which are accountable for sensing velocity and change in velocity.

In a similar way, SA domes on crocodiles assist them to sense constant flows which impart a steady pressure on the dome, whereas RA domes would aid in sensing oscillating flows. Considering this aspect, an ISO-inspired sensing system should have two types of receptors so that stimuli of interest are comprehensively captured.

2.5 A few lessons from lateral line-inspired sensing systems

As mentioned in section 2.2.1, apart from crocodiles, fishes and harbor seals also use passive hydrodynamic passive sensing. Fishes have a sensing system called lateral line and harbor seals possess whiskers, to carry out hydrodynamic sensing. Amongst the two, lateral line system is a complete sensing system with various components for sensing and noise reduction. It is also probably the most well-studied mechanoreception system and has inspired a wide range of works by researchers. It is worth understanding the major areas of the research aimed at making sensing systems inspired from lateral line. This understanding will help in taking up a comprehensive approach to build an ISO-inspired sensing system.

Lateral line is a sensory system made up of arrays of pillar like structures called neuromasts, which assists fishes in sensing flows and disturbances around the fish in the water. Lateral line in fish is one of the most studied sensory systems in aquatic animals. The confirmation of mechanoreceptive functionality of lateral line in fish dates back to the first quarter of the twentieth century [43]. Over last century, there has been comprehensive research done on the biological front, to study and explain the structure, functioning and underlying working principles of lateral line [16, 44, 45]. In general, lateral line (shown as dotted red line in Figure 2.9(a)) is comprised of two types of pillar like structures called neuromasts, each of which has hair cell receptors embedded within it. Superficial neuromasts (shown in Figure 2.9(b)), present on the skin of fish, exposed directly to the water flow, assist in sensing the velocity of flow. They are standing pillar structures which sense the flow velocity through their bending due to drag force applied by the flow. Canal neuromasts (shown in Figure 2.9(c)), which are located within canal structures beneath the skin, sense gradient in pressure. They are exposed to the flow of water through the pores on the canal and are activated when there is a pressure difference between the two adjacent

pores. Lateral line plays an important role in several behavioural functions of fish such as surface feeding, schooling, obstacle avoidance and subsurface detection of prey. The inspiration from lateral line has resulted in various developments ranging from novel sensors [46-49] to application of artificial algorithms for object and flow detection using arrays of these sensors [50-54].

Figure 2.9: Lateral line system: (a) A photograph of the blind cave fish *Astyanax fasciatus* with its lateral line marked with a dotted red line. (b) Schematic of superficial neuromasts which are present on the skin surface and (c) Schematic of canal neuromasts which are present within a canal, beneath the skin. Both types of neuromasts have cupula covering sensory hair cells.

2.5.1 Neuromast-inspired sensors

First area of lateral-line-inspired works is associated with development of sensors to mimic the neuromasts in lateral line. These bio-inspired designs incorporate a pillar-like standing structure which functions as cupula and a sensing element which functions as sensory hair cells. Figure

2.10 depicts a neuromast inspired sensor with a bendable structure as presented by Chen et al. [55]. A 700 μm tall polymer hair cell sits on a cantilever beam which has silicon piezoresistive strain gauges patterned at its base. Due to drag force on the hair, the cantilever bends and the flow is measured in terms of change in the resistance of the strain gauges. The flow sensor works similar to the superficial neuromast in which bending of neuromast causes hair cells to generate signal.

Figure 2.10: A scanning electron micrograph of a biomimetic neuromast which is made up of a polymer hair standing on a cantilever beam [56].

The sensor described above is just to provide a gist of neuromast-inspired sensors. Variety of these sensors and respective inspirational features of lateral line are listed in table 2.1.

2.5.2 Mechanical filtering mechanism of canal structure

The other interesting aspect of lateral line is the canal structure. The canal structure plays the role of a high pass filter, ensuring that the low frequency noise caused due to steady flow and movement of the fish itself does not reach the canal neuromasts. There can be flow inside the canal only when there is a pressure difference between the canal pores. Kottapalli et al. constructed a polydimethylsiloxane (PDMS) canal structure with pores on top and flow sensors placed at positions between the two pores (shown in Figure 2.11(a) and 2.11(b)) [57]. The canal

structure demonstrated dc flow filtering capabilities by masking the steady flow signal from affecting the neuromasts inside the canal.

Figure 2.11: Bio-inspired canal structure: (a) Schematic of a bio-inspired artificial canal structure that functions as a mechanical filter [57]. (b) Photograph of a flexible canal with pores, made up of PDMS [57].

2.5.3 Using array of sensors for flow sensing

Lateral line consists of arrays of these sensors; hence apart from development of individual sensors, another area of focus has been, how arrays of these sensors can be used to detect flows and disturbances around underwater vehicles and localization of moving objects in its vicinity. Researchers have used lateral line-inspired arrays of commercially available pressure sensors, mounted on AUVs to obtain information about flows which would help AUVs in their orienting and maneuvering. For example, Salumae and Kruusmaa [58] used pressure sensor arrays inspired from lateral line to improve the control of an underwater robot. Figure 2.12 shows a schematic of an underwater robot with an array consisting of pressure sensors S1, S2, S3, S4 and S5 on the rigid head of the robot. The outputs of the sensors in the array can be utilized to discriminate between steady and turbulent flows; to detect the orientation of the vehicle; to measure the speed

of the flow and to estimate the position of the robot in the wake of an object. This information can be utilized in making the control and maneuvering of the robot more energy efficient.

Figure 2.12: Schematic of an underwater robot with an array of 5 sensors (S1-S5) on its front end. This configuration of sensors was utilized for flow sensing and improving maneuvering of an underwater robot [58].

2.5.4 Using array of sensors for object detection

An important aspect of lateral-line-inspired developments is employing array of sensors for detecting movement of objects in vicinity and determing various parameters associated with the movement. For example, Fernandez et al. [59] towed a cylindrical rod of diameter d along a linear array of four pressure sensors at a distance s from the array as shown in figure 2.13(a). From the patterns of signals generated due to passing of the rod, they were able to detect the speed, direction and diamter of the rod.

Figure 2.13: Schematic of experimental setup: (a) Four pressure sensors (1 to 4) housed like lateral line array and a cylinder of diameter d is towed parallel to the linear array. (b) Close-up of pressure ports [59].

2.5.5 Employing intelligent processing algorithms

It is important to extract meaningful information from the data collected by the sensors, in efficient and quick manner. This can be achieved through intelligent signal processing algorithms, statistical methods and machine learning techniques. For example, Pandya et al. [52] employed an array of 16 neuromast-inspired sensors (shown in Figure 2.14) to apply algorithms for locating an oscillating dipole source in water. They demonstrated that the application of the algorithms to signals received from the array of the artificial lateral line can result in tracking the movement of the oscillating dipole.

Figure 2.14: An optical micrograph of an artificial lateral line array comprised of 16 hot wire anemometer sensors [52].

The examples mentioned in the previous sections demonstrate that bio-inspiration can be drawn from different aspects of a biological sensing system resulting in different applications. For example – different aspects of lateral line that have influenced human-made sensing systems are – i) structural variation of neuromasts i.e. different shapes of superficial and canal neuromasts, ii) functional variation of neuromasts i.e. the fact that superficial and canal neuromasts are specialized in sensing a specific type of stimulus iii) mechanical filtering capability of the canal structure iv) the fact that lateral line is composed of arrays of neuromasts. On the other hand, the feature of harbor seal whiskers that has left its impact is primarily the undulated structure of the whiskers. Table 2.1 provides chronologically arranged compilation of various artificial underwater hydrodynamic sensors inspired by the aforementioned features of the biological sensing systems – lateral line and harbor seal whiskers.

Table 2.1: Notable attempts to fabricate underwater flow sensors which are inspired by sensory organs of aquatic animals.

Sr. No.	Authors	Bio mimicry / inspiration	Sensing element/ mechanism	Dimensions/sensitivity	Image
1	Peleshanko, Julian et al. (2007) [46]	Lateral line - superficial neuromasts	Flow sensing: Haircell/ piezoresistive flow sensor	Height of the pillar = 1 mm Lowest detectable velocity = 75 $\mu\text{m/s}$
2	Yang, Chen et al. (2006) [50]	Lateral line - superficial neuromasts	Flow sensing: Pillar/ Thermal hot wire anemometry	Elevation of the wire = 600 μm Lowest detectable velocity = 200 $\mu\text{m/s}$
3	Asadnia, Kottapalli et al. (2013) [60]	Lateral line array	Flow sensing: piezoelectric sensor array	Gap between two sensors in array = 7 mm Lowest detectable velocity = 3 mm/s
4	Kottapalli, Asadnia et al. (2016) [61]	Cupula encapsulating neuromast	Flow sensing: Hydrogel cupula increases drag force experienced by the flow sensing element	Sensitivity enhanced by factor of 3.5-5, Lowest detectable velocity = 18 mm/s Sensitivity = 77 mV/(m/s)
5	Kottapalli, Asadnia et al. (2014) [57]	Lateral line - both canal and superficial neuromasts	Flow sensing: Pillars/ piezoresistive flow sensor	Pillar height = 2.7 mm Sensitivity = 3.3 mV/(m/s)
6	Nawi, Manaf et al. (2014) [62]	Lateral line – Canal Neuromast	Dome shaped cupula/ capacitive flow sensor	Dome radius = 3.2 mm Lowest detectable velocity = 10 cm/s
7	Beem, Hildner et al. (2013) [63]	Harbor Seal whiskers	Whisker inspired undulated pillar/ flow sensor	Length of the whisker = 275 mm Cross flow diameter = 15.9 mm
8	Fan, Chen et al. (2002) [64]	Lateral line - superficial neuromasts	Flow sensing Cantilever with pillar / piezoresistive	Height of the vertical structure = 820 μm

9	Salumae and Kruusmaa (2013) [58]	Lateral line array	Pressure sensor array	Sensitivity of the commercial sensor used = 0.1 Pa
10	Kottapalli, Asadnia et al. (2012) [48]	Lateral line array	Pressure sensor array/ piezoresistive	Gap between two sensors in array = 4 mm Sensitivity = 14.3 $\mu\text{V}/\text{Pa}$
11	Venturelli, Akanyeti et al. (2012) [65]	Lateral line array	Pressure sensor array	Gap between two sensors in array = 1 cm Sensitivity = 56 mV/bar
12	Lagor, DeVries et al. (2013) [53]	Lateral line - canal neuromasts	Pressure sensor array	One pressure sensor on either side of the robotic fish is used.
13	Kottapalli, Asadnia et al. (2014) [57]	Canal structure	High pass mechanical filter	Filters out effect of DC flow of speeds 75, 175 and 275 mm/s

2.5.6 Takeaways from past research on lateral-line inspired sensing system

Being aware about different aspects of research related to lateral-line inspired system can help in deciding priorities and focus of this project. Overall development plan for an ISO-inspired sensing system can have following areas of research.

1. Development of dome shaped sensors inspired from ISOs associated with SA and RA receptors.
2. ISO-inspired domes for flow sensing applications.
3. ISO-inspired domes for object detection applications.
4. Development of a mechanical filtering mechanism inspired from Lamellated corpuscles.
5. Arrays of ISO-inspired domes for aforementioned applications

6. Employing different algorithms, statistical tools and machine learning techniques for extracting information from the data read by ISO-inspired domes

Each of the area mentioned in the aforementioned list incorporates wide range of possibilities in itself and only certain areas are incorporated in this project. Broadly, the first three areas in the list can be considered to be foundational and the next three areas can be considered as higher level objectives. For this reason, the focus of this project would be in developing ISO-inspired dome shaped sensors, investigating their flow sensing, direction detection ability and exploring their object detection capabilities.

2.6 Conclusions

The literature review helped in gaining a broader perspective about the field of bio-inspiration and biomimetics. It is a very effective approach to find efficient and sustainable solutions to a wide range of problems faced by human civilization.

ISOs on crocodile are fascinating multisensory organs with ability to sense pressure, temperature and pH value of water. The multi-sensing capabilities make them ideal candidates as ‘an inspiration for artificial sensing system’ that would provide AUVs with comprehensive data about surroundings. However, research community is yet to acquire a complete knowledge about all the sensing mechanisms, their structural aspects, neural aspects and their probable interdependence. Amongst all the sensing capabilities of ISOs, pressure sensing is the most investigated one. Biological researchers have successfully studied structural and functional properties of ISOs pertaining to pressure sensing. This work draws inspiration from two structural features and one functional feature of ISOs. The first noticeable structural feature of ISOs is its hemispherical/dome shape. The second structural feature is that the surface of an ISO

is covered with mechanoreceptors and free nerve endings that carry out the task of sensing the mechanical stimulus. Both these structural features together form a hemispherical array of mechanoreceptors. An ISO-inspired sensing system can be envisioned to be consisting of several dome structures and each of them is embedded with pressure sensors. The third ingredient of bio-inspiration is associated with functional aspect of having two different kinds of receptors namely, SA and RA, for sensing steady state and oscillating pressure stimulus respectively.

The literature review also helped in understanding various areas of research associated with a bio-inspired passive hydrodynamic sensing system, through the example of lateral line-inspired works. The primary focus of this work would be to develop the dome shaped sensors and to study their flow sensing and object detection abilities. On this foundation, in future, the work can be improved to have mechanical filtering and smart decision making algorithms to obtain a complete ISO-inspired passive hydrodynamic sensing system for AUVs.

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3

BIO-INSPIRATION AND PROOF OF CONCEPT

This chapter discusses details of the bio-inspiration drawn from ISOs of crocodiles and then goes on to describe development of ISO-inspired artificial slowly adapting (SA) and rapidly adapting (RA) domes. Subsequently, it elaborates proof of concept experiments conducted to demonstrate the direction detection and flow sensing abilities of SA and RA domes for steady and oscillating stimulus respectively. Furthermore, sea trial experiments to explore the viability of the SA domes in real life scenario are also described.

3.1 Introduction

In the quest for developing an ISO-inspired passive hydrodynamic sensing system, the first step is to fabricate dome shaped sensors which would carry out sensing similar to slowly adapting (SA) and rapidly adapting (RA) receptors. Subsequent task on agenda is to test the fabricated domes for flow sensing and direction detection abilities. Both these tasks together can shed more light on feasibility of employing ISO-inspired domes for the sensing purpose. Therefore first two steps are important from perspective of obtaining proof of concept.

3.2 Bio-inspiration

Before delving into design and fabrication of ISO-inspired domes, it is worth to revisit the bio-inspiration drawn from ISOs. Figure 3.1(a) depicts a schematic of structure of an individual ISO, drawn based on the schematics presented in [1] and [2]. Below the outer layers of the epidermis of the skin that covers ISOs, discoid mechanoreceptors and free nerve terminals are positioned, which together execute the task of receiving mechanical stimulus. Mechanoreceptors in ISOs are categorized into two types based on the receptor cells they are associated with - i) SA receptors are associated with Merkel cells [1],[3] and ii) RA receptors are associated with Lamellated corpuscles [1],[2]. The two types of receptors cater to different kinds of stimuli – SA receptors are suitable for sensing steady flows and variations in them whereas RA receptors are suitable for sensing oscillating pressures caused due to fast movements of aquatic animals e.g. rapid movements of a swimming fish. Interestingly, the lateral line in fish is also equipped with two types of receptors which are accountable for sensing velocity and change in velocity. The response from superficial neuromasts is proportional to the relative velocity between the fish and the surrounding water, whereas, the response of canal neuromasts is proportional to net acceleration [4]. This underlines the fact that passive mechanoreceptive sensing systems

constitute different types of receptors which function based on principle of ‘division of labour’, each specializing in responding to a particular type of stimulus.

Figure 3.1: (a) Schematic of the structure of an individual ISO showing discoid and free nerve mechanoreceptors under the skin of dome (based on schematics presented in [1] and [2]). (b) Schematic representation of the proposed dome shaped sensor in which the pressure sensors placed on the surface of the dome would play the role of mechanoreceptors.

As explained in the previous chapter, the inspiration from the ISOs of crocodiles is associated with three aspects. Firstly, the dome shape of the ISOs on crocodiles; the advantage of dome shape is that due to its spherically symmetric structure, it can provide information in three dimensions with an isotropic reception of stimulus. From the patterns and combinations of the pressure variation read by the pressure sensors on the dome surface, the direction of the origin of the disturbance can be determined. Secondly, the presence of mechanoreceptors on the dome surface; the epidermal layer of each ISO is equipped with mechanoreceptors which are spread throughout the surface as shown in Figure 3.1(a). Therefore an ISO-inspired device would have a dome structure with pressure sensors embedded on its surface as shown in Figure 3.1(b). Third aspect of the inspiration is, the ‘division of labor’ between slowly and rapidly adapting receptors. Drawing inspiration from SA and RA receptors, two types of dome structures are constructed –

SA dome equipped with piezoresistive sensors to sense steady pressures and RA dome embedded with piezoelectric sensors to sense oscillating pressures.

3.3 Design and Fabrication of artificial SA and RA domes

SA and RA domes are constructed by mounting MEMS piezoresistive pressure sensors and MEMS piezoelectric pressure sensors respectively, on a stiff dome-shaped base structure which is built using 3D printing technology. The piezoresistive sensors are reported in [5] and the piezoelectric sensors are reported in [6]. As the footprint of the pressure sensors to be used on SA (piezoresistive sensors) and RA (piezoelectric sensors) domes is different, two different designs of the domes are created. A hollow dome of radius 10 mm and shell thickness of 2 mm is designed with slots to accommodate 5 sensors. The slot dimensions for SA dome and RA dome are $6\text{ mm} \times 3.5\text{ mm}$ and $3\text{ mm} \times 3\text{ mm}$, respectively. Two through holes are provided for each slot to house the connecting wires for each sensor. A 3D printed hollow cylinder with outer radius of 10 mm, inner radius of 8 mm and length 40 mm is attached to the dome to provide path for connecting wires and support for the dome. The material used for 3D printing the dome and the cylinder is polymer PlasCLEAR (Asiga Inc). Tensile strength of the material is 52.6 MPa which is sufficient to provide the stiffness required so that the dome does not deform when it is subjected to hydrodynamic pressures (typically of the order of a few hundred Pascal).

The MEMS piezoresistive sensor has footprint of $5\text{ mm} \times 3\text{ mm}$ and it has $25\text{ }\mu\text{m}$ thick liquid crystal polymer (LCP) membrane on which gold piezoresistors are deposited in zig zag pattern as shown in Figure 3.2(a). The details of the design and fabrication of this pressure sensor are described in [5]. The membrane bends when pressure is applied, which causes a change in the resistance of the piezoresistors and the pressure value can be read in terms of voltage across the

piezoresistor using a Wheatstone's bridge circuit. The output voltage of a piezoresistive sensor remains constant throughout as long as a static pressure is applied on its diaphragm. In crocodiles, the steady levels of mechanical stimuli are sensed by SA receptors, which keep on firing throughout the presence of the stimulus that is applied to them. This shows that the response of piezoresistive sensors resembles the response of SA receptors from the perspective of sensing a steady mechanical stimulus.

The piezoelectric pressure sensor has footprint of $2\text{ mm} \times 2\text{ mm}$ and it has a silicon membrane on which Lead Zirconate Titanate (PZT) layer is present which functions as sensing element. There is a bottom floating electrode beneath the PZT layer and top electrode is patterned as a central circular and outer ring electrode as shown in Figure 3.2(b). The bottom floating electrode ensures that the electric field lines first go from the ring electrode to the bottom electrode and then to the top circular electrode. This ensures that the effect of stresses with opposite polarity is added and entire area of top electrode is exploited. The fabrication steps for the micro-diaphragm PZT pressure sensor are described in [6]. A piezoelectric sensor responds only to oscillatory or dynamic pressures and not to a static pressure. For dynamic pressures the diaphragm bends and owing to piezoelectric effect, corresponding signal is generated at the electrodes. If a static pressure is applied, potential difference is generated between the electrodes only at the moment of application of the pressure. The charges are lost due to leakage and there is no further signal generated for the static pressure. This resembles to how RA receptors fire when there is change in the stimulus level and not when the level of the stimulus is constant.

The pressure sensors are positioned on the dome in the provided sockets. Five sensors on each dome are labeled as 'East', 'West', 'North', 'South' and 'Center'. Sensors other than the 'Center' sensor (which is at the apex of dome) are at 45° latitude with respect to the base of the

hemispherical dome. Wires are passed through the through-holes on the dome and soldered to have the contacts on the dome surface. After soldering connecting wires, dome is filled with Polydimethylsiloxane (PDMS) and cured for 3 hours at 75°C. PDMS can support the wires and prevent them from being in contact with the neighboring wires. Subsequently, the dome is attached to a hollow cylinder to provide support to the structure and path for connecting wires.

Once the dome is attached to cylinder, the pressure sensors are placed on the dome using nonconductive epoxy - EPO TEK H70E (Epoxy Technology Inc.). Afterwards the devices are fixed to the dome, the contact pads of each device are connected to the respective connecting wires using conductive epoxy - EPO TEK H20E (Epoxy Technology Inc.).

Figure 3.2: Bio-inspired MEMS RA and SA domes: (a) Piezoresistive LCP membrane pressure sensor with gold piezoresistor on LCP membrane (b) micro-diaphragm piezoelectric pressure sensor with top circular and ring electrodes (c) SA dome constructed using LCP pressure sensors (d) RA dome constructed using PZT pressure sensors.

3.4 Proof of concept experiments

This subsection describes the experiments carried out to examine the direction detection ability of both – SA and RA domes. The experiments for SA domes are carried out in wind and water tunnel so that the dome can be subjected to steady flows, whereas experiments for RA dome are conducted in a water tank with an oscillating sphere as a source of oscillating pressure stimulus.

3.4.1 Direction detection using SA dome

The direction detection experiments for SA dome are conducted in water tunnel. Figure 3.3(a) shows a schematic of experimental set up in which an SA dome is placed in the water flow inside a tunnel, using a support and clamp arrangement. Each of the piezoresistive sensors on SA dome is connected to external Wheatstone bridge circuit to convert the resistance change into voltage change. The sensor is operated as one arm of the Wheatstone bridge circuit. The other resistances of the circuit are chosen to be the same as the resistance of the gold piezoresistor which is approximately $220\ \Omega$, in order to maintain a zero output voltage when no external pressure acts on the membrane. The Wheatstone bridge circuit is biased with constant voltage of 5 V, and the signal from the sensor is acquired by LAB VIEW software using a National Instruments data acquisition (NI-DAQ) system USB-6289 M-series model as depicted in Figure 3.3(b).

Figure 3.3: Experimental setup: (a) Schematic of the experimental set up showing the SA dome fixed inside water tunnel (b) Block diagram depicting Wheatstone's bridge circuit with one sensor on SA dome operating as one arm of the circuit and other components in the experimental setup.

3.4.2 Direction detection using RA dome

RA dome assembled using the PZT pressure sensors is tested for its ability to determine the direction of the origin of a disturbance generated by an oscillating sphere (dipole). It is known that the pressure variations due to a dipole are similar to the biological relevant pressure

variations caused by swimming animals [7]. A stainless steel sphere of 15 mm diameter is attached to a minishaker (model 410, B & K, Norcross, GA) through a rod of 2 mm diameter (as shown in Figure 3.4(a) and 3.4(b)). The minishaker is driven by sinusoidal signals generated by a function generator amplified through a power amplifier (Type 2718, B & K). The signal generator is set to generate signals of frequency of 30 Hz and at fixed amplitude of $250 \text{ mV}_{\text{rms}}$. The choice of frequency is made considering the fact that typical underwater oscillating pressure signals are of frequencies below 100 Hz [8] and RA receptors in crocodiles in particular, demonstrate maximum sensitivity in the frequency range 10 to 35 Hz. This choice also ensures that the 50 Hz electronic noise is distinguishable from the output signal and can be easily filtered out. A water tank of dimensions $40 \text{ cm} \times 25 \text{ cm} \times 30 \text{ cm}$ is filled with deionized water and the RA dome attached to a supporting cylinder is clamped inside the water tank as shown in Figure 3.4(a). Each of the five sensors on the dome is positioned beneath the oscillating dipole and the distance between the dome and the dipole is increased from 5 mm to 30 mm in the steps of 5 mm. For each step the outputs of all the five sensors are recorded without any amplification, signals corresponding to 30 Hz frequency are analysed and the normalized output patterns are plotted.

Figure 3.4: Experimental setup depicting the position of dipole and dome: (a) Orientation of the dome is changed to position different sensors under the dipole. (b) Block diagram showing all the components in the experimental set up and interconnections.

3.5 Experimental results and discussions

The dissimilarities in sensors, caused during fabrication processes (eg. variation in diaphragm diameter owing to notch effect during DRIE backside etching of Silicon) and packaging processes may result in differences in responses of the 5 sensors to the same stimulus. A calibration process is carried out to bring parity amongst the five sensors on a dome. The output values mentioned in the discussions are calibrated values.

3.5.1 Direction detection using SA dome

The goal of the first set of experiments is to confirm the ability of the SA dome in detecting steady state flows. The second set of experiments are aimed at confirming if the dome continues to show its directional behavior when it is placed on a flat surface considering the possible deterrent effect of boundary layer in accessing the maximum speed of the flow which lies outside the boundary layer. The pressure sensed by a sensor placed in a flow of water is a combination of static and dynamic pressure. The static pressure is caused due to the weight of the water column above the sensor whereas dynamic pressure is due to the force imparted by the flow of water. The output of a pressure sensor when there is no flow corresponds to the static pressure and it is nullified by making output curves for all five sensors coincide at the time when the water is made to flow. Hence the change in the output of the sensors corresponds only to dynamic pressure.

Figure 3.5(a) depicts normalized outputs of five sensors when SA dome is subjected to water flow with a constant flow velocity of 0.02 m/s when ‘East’ sensor is facing the flow. The sensor which faces the flow (i.e. ‘East’) shows the maximum output and the one which is on the opposite side (‘West’) shows the minimum output. The outputs of the remaining three sensors lie

in between the maximum and minimum values mentioned above. Polar plot in figure 3.5(b) expresses the directionality of SA dome in water flow. In the polar plot, the distance of a blue dot from the center represents the output at the respective sensor. The plots depict output (in mV) of each of the five sensors on SA dome, when 'East' sensor is facing the flow. The dots representing outputs of 'East', 'West', 'North' and 'South' are connected by lines and the dot representing output of 'Center' is shown within the quadrangle. The iso-contours in the polar plots represent output values mentioned on respective iso-contours. Bar graph in figure 3.5(c) shows mean outputs of each sensor with error bars being the standard deviation of 3 runs. From figure 3.5(c) it can be noted that the difference in the outputs at North and South, is about 13% of the difference in outputs at East and West. It implies that the difference in South and North is significantly lower than the difference in East and West, indicating direction detection ability of the dome. However, considering the identical positions of 'North' and 'South' with respect to the incoming flow, they are expected to show same output. The discrepancy between them could be attributed to slight misalignment of dome orientation with respect to the incoming flow and irregularities caused by contacts of the sensors on the dome surface.

Figure 3.5: Flow sensing abilities of SA dome: (a) Outputs at five sensors for the case when ‘East’ sensor is facing the flow in water tunnel. (b) Polar plot for the case when ‘East’ sensor is facing the flow of speed 0.02 m/s. The iso-contours represent the output values in mV and the output corresponding to ‘Center’ sensor is denoted by the blue dot within the quadrangle. (c) Averages of the outputs of five sensors with respective standard deviations shown as error bars.

Flows over a hemisphere have different velocity profile regions around the hemispherical surface. At this point, it would be appropriate to refer to work done by researchers on visualization of flows over hemispherical obstacles. The Reynolds number for this flow is 400 and the experiments described next in same section are conducted for Reynolds number of up to 4000. Considering that the flows with same Reynolds numbers are dynamically similar, the

experimental results can be compared with experiments from literature which are conducted with similar Reynolds numbers. Figure 3.6(a) depicts velocity profile of a flow over a hemisphere for laminar flow ($Re = 800$), obtained through Particle Image Velocimetry technique by Goharzadeh et al [9]. The streamlines show that there is a stagnation region where flow reaches the hemisphere and a separation zone where flow separates from the hemisphere to form wake. Stagnation region has higher pressure whereas the wake region has lower pressure. Figure 3.6(b) shows a flow profile obtained by Fedrizzi et al [10], for air flow over a dome, clearly depicting the flow separation line. Though this particular work is associated with higher Reynolds number (6.36×10^4), from figure 3.6(a), the flow separation is very evident at Reynolds numbers of the order of 800 too. A clear line of flow separation can be seen in the figure 3.6(b). If this line is correlated to the SA dome, ‘Center’ and two lateral sensors would lie on the line. As the flow is separating from the surface, the pressure coefficient along the line is similar, making the three sensors along the line show similar outputs.

Figure 3.6: Flow over a hemisphere: (a) Flow velocity profile for a flow over 30 mm diameter hemisphere for $Re = 800$ [9] (b) Surface shear flow visualization of flow over hemisphere ($Re = 6.36 \times 10^4$) [10].

Figure 3.7 (a) – (f) show polar plots when ‘North’ sensor faces water flow of speeds 0.03 m/s ($Re = 600$), 0.05 m/s, 0.07 m/s, 0.10 m/s, 0.15 m/s and 0.20 m/s ($Re = 4000$), respectively. The values shown in each of the polar plots are means of five runs. The polar plots show that the

dome can detect direction of the flow for all the flow speeds. However the pattern shows that the direction detection ability of the dome would diminish as speed increases.

Figure 3.7: Polar plots for the case when ‘North’ sensor is facing the flow of speeds (a) 0.03 m/s, (b) 0.05 m/s, (c) 0.07 m/s, (d) 0.10 m/s (e) 0.15 m/s and (f) 0.20 m/s. The iso-contours represent the output values in mV and the output corresponding to ‘Center’ sensor is denoted by the blue dot within the quadrangle.

Ratio of outputs at ‘North’ and ‘South’ can be considered as a measure of directionality of the dome. The ratio is around 2.6 for speed 0.05 m/s, which drops to 1.87 for speed 0.1 m/s and to 1.15 for speed 0.2 m/s. The ‘North’ which is facing the flow, shows rapid increase in output for low speeds. For higher speeds, its rate of increase reduces and it approaches saturation. On the

other hand the output of South shows gradual increase for lower speeds and slightly steeper increase for higher flow speeds. This variation in directionality is due to the fact that sensor facing the flow shows tendency towards saturation for higher speeds. In fact, in terms of pressure coefficients, the directionality should improve with flow speed. This aspect will be discussed later with reference to pressure coefficient plot shown in figure 3.8.

To check if the directional information is statistically significant, a paired samples t-test is conducted to check how significantly the outputs of North and South sensors are different for each speed. The number of runs or observations for each speed is 5 ($df = 4$). Since normalized outputs of two sensors are being compared, the outputs of the two sensors for a stimulus can be treated as the output of one sensor for two different positions on the dome for the same stimulus. Hence paired t-test is used for the analysis. It is observed that for all the speeds the output of 'North' is significantly greater than that of 'South' ($p < 0.01$). Though the polar plot in figure 3.7(f) for speed of 0.2 m/s may not seem to be providing directional information, it is observed that there is a significant difference between output at North (Mean = 9.48 mV, SD = 0.12 mV) and output at South (Mean = 7.98 mV, SD = 0.2 mV), conditions; $t(4) = 23.38$, $p < 0.01$. Similarly, comparison of North and Center and, North and East depicted significant differences ($p < 0.01$). Comparison between East and West showed that the difference between them is insignificant ($p > 0.01$). East and West show similar outputs owing to their symmetric position with respect to the flow direction.

From these experimental results, one observation has been consistent. If flow is coming from 'East', the hierarchy of outputs at East, Center and West on the dome is, $E_{\text{output}} > C_{\text{output}} > W_{\text{output}}$ (Figure 3.8(a)). It would be interesting to compare this pattern with results from literature, which

shed more light on various flow regions and pressure coefficient over the surface of a hemisphere.

Wood et al [11], in their work visualized the flow over a hemisphere and listed down various characteristic flow regions as shown in figure 3.8(b). These regions can be correlated to pressure variation on the surface of the hemisphere. Relative pressures on the surface of a hemisphere facing a flow can be expressed in terms of a dimensionless quantity called pressure coefficient. Pressure coefficient (C_p) is defined as,

$$C_p = \frac{p - p_\infty}{q_\infty}, \quad \text{..... (3.1)}$$

where, p is surface static pressure, p_∞ is free stream static pressure and q_∞ is free stream dynamic pressure. Taniguchi et al [12] studied pressure variation on surface of a hemisphere for different Reynolds numbers ranging from about 200 to 2000. Figure 3.8(c) shows a graph of C_p value curves for different Reynolds numbers from [12] plotted along the arc represented by dotted red line in figure 3.8(a). Fedrizzi et al [10] have also shown a similar trend in pressure coefficient through their experimental work for higher Reynolds numbers as well.

Figure 3.8: a) Schematic showing side view of hemisphere, direction of approaching flow and red dotted line represents the arc along which C_p values are plotted in 3.8(c). (b) Visualization of flow around a hemisphere and characteristic flow features – 1. Horseshoe vortex system, 2. Stagnation area, 3. Acceleration of the flow, 4. Separation point, 5. Dividing streamline, 6. Shear layer vorticity [11] (c) Pressure distribution over the plane of symmetry (along the red dotted arc in figure 3.8(a)) of the hemisphere in terms of pressure coefficient [12].

Region 1 in figure 3.8(b) is characterized by horseshoe vortices. If correlated with plot in figure 3.8(c), this region corresponds to initial part of the pressure coefficient plot, where the value of C_p is lower than that at stagnation region. From the plot, the region around 30-40 degrees shows higher C_p , which implies that the region is closer to stagnation region (i.e. region 2 in figure 3.8(b)) and most of the kinetic energy of flow is converted to pressure. If compared to SA dome, this region corresponds to ‘East’ sensor that shows the highest output amongst all the sensors.

As flow moves from stagnation point towards the apex of the dome, velocity increases and therefore pressure decreases, resulting in reduction in pressure coefficient (region 3 in figure 3.8(b)). At around 80-90 degrees in the plot, C_p shows a minimum. In figure 3.8(b) this region 4 is characterized by the separation of flow. When compared with SA dome, the region corresponds to ‘Center’ and it explains why ‘Center’ has lower output than ‘East’.

Region 5 in figure 3.8(b) shows the wake of hemisphere which has recirculation region and outer flow field. As far as surface of the dome is concerned, the value of C_p increases slightly for the angle around 130 – 140 degrees, which corresponds to ‘West’. So after flow separation, the pressure along the surface doesn’t rise much and remains close to the value at the apex. However the plot hints that output at ‘Center’ should be slightly lower than that at ‘West’. But experimental results have shown the other way i.e. ‘West’ has always shown lower output than ‘Center’. This discrepancy could be due to the fact that after placement of sensors on the dome, the outline of the dome surface doesn’t remain an ideal smooth hemispherical arc. ‘Center’ sensor makes the apex flat rather than a continuous curved region. This may lead to variations in flows around the dome. The flows around SA dome can be investigated further through flow visualization techniques like Particle Image Velocimetry.

The pressure coefficient plots in figure 3.8(c) are drawn for Reynolds numbers ranging from 200 to 2000. Reynolds number is proportional to flow speed and higher the Reynolds number, higher is the disparity in maximum and minimum of C_p values. It implies that for higher flow speeds the differences in pressures across the surface of the dome should increase and therefore improve the directionality. However the response of SA dome to the increasing flow speeds (figure 3.7) shows reduced directionality for higher speeds. As mentioned earlier, the reason behind this discrepancy is the saturating response of individual sensor for higher flow speeds.

From the results depicted in Figure 3.5 and Figure 3.7, the ability of SA dome to identify the direction of a steady flow, through the pattern of the outputs of five pressure sensors, is evident. For real life application, the domes are to be placed on the surface of AUV and the boundary layer formed on the surface is a concern because a dome completely immersed inside boundary layer will not have access to the free-stream flow speed; hence it is important to investigate the effect of boundary layer on the directionality of SA dome. To check the directionality of the dome immersed in the boundary layer, the dome was placed on a slab such that the leading edge is 10 cm away from it.

Boundary layer thickness is given by,

$$\delta = \frac{4.91 \times x}{\sqrt{Re_x}} \quad \dots\dots (3.2)$$

where, δ is boundary layer thickness, x is distance from leading edge, and

Re_x is Reynolds number which is given by,

$$Re_x = \frac{\rho V x}{\mu} \quad \dots\dots (3.3)$$

where, ρ is density of water, V is free-stream flow velocity, μ is dynamic viscosity

Theoretical calculations show that for a leading edge of 10 cm and water flow speed of 0.02 m/s the boundary layer thickness is about 1 cm, which is equal to the height of the dome. Even for this case the dome demonstrated good directionality. Figure 3.9 depicts the comparison of directionality of dome without a boundary layer against the case when it is affected by a boundary layer. Figure 3.9(a) shows the sensors outputs for the case when ‘South’ sensor is facing the flow and the dome is not placed on a flat surface, whereas Figure 3.9(b) shows a plot for the case when the dome is placed on a flat surface with the leading edge at a distance 10 cm. Figures 3.9 (c) and 3.9 (d) depict average output values of each sensor for three runs, in the form of bar graphs and the error bars represent standard deviation. From comparison of bar charts in

figure 3.9(c) and 3.9(d), sensors other than ‘Center’ show reduction in respective outputs by at least 35%, whereas ‘Center’ shows reduction by only about 18%. This could be an indicator of the fact that ‘Center’ is close to boundary layer edge, whereas the rest of the sensors are inside the boundary layer. This can be further analyzed quantitatively, through either flow visualization experiments or fluid-structure interaction simulation. Though due to the boundary layer the magnitude of the outputs of all the sensors have reduced, directionality of the dome is still evident. This also implies that position of a dome on AUV surface should be taken into account while interpreting the information received by the dome.

Figure 3.9: Effect of boundary layer on sensing performance: (a) Polar plot for the case when 'South' sensor is facing the flow in the water tunnel. (b) Polar plot for the case when 'South' sensor is facing the flow and dome is placed on a flat surface with leading edge at 10 cm distance from the dome. (c) and (d), bar charts showing average values of output of each sensor for 'dome not on surface' and 'dome on surface' cases respectively for three runs. Error bars represent standard deviation.

3.5.2 Direction detection using RA dome

Figure 3.10 depicts outputs at five sensors when ‘Center’ sensor is placed beneath the oscillating dipole and ‘Center’ shows the maximum peak to peak output amongst the five sensors.

Figure 3.10: (a) Output at five sensors when ‘Center’ sensor is below the oscillating dipole at 5 mm distance. (b) Schematic representation of a dipole oscillating at origin and observation point P at angle θ and distance r from origin. In top right corner the direction of oscillation is denoted. (c) Geometry measurements for the case where dipole sphere is at 5 mm distance from the dome.

This observation can be explained through equation for pressure due to an oscillating dipole. A dipole oscillating (Figure 3.10(b)) in a fluid medium generates pressure field which is given by,

$$p(r, \theta) = - \frac{\rho \omega a^3 U_o \cos(\theta)}{2r^2} \quad \dots\dots (3.4)$$

where, a , ρ , r , θ , ω and U_o are dipole diameter, density of fluid, observation distance, angle made by observation direction with dipole oscillation direction, angular frequency and initial vibrational velocity amplitude, respectively [13]. For the sensor directly beneath the oscillating dipole, angle θ is zero and distance r is least among all the five sensors and therefore the pressure sensed by the sensor is maximum. Figure 3.10(d) depicts geometry measurements for the case where ‘Center’ is beneath dipole.

For ‘Center’, $\theta_1 = 0^\circ$ and $r_1 = 5$ mm. From geometry of the dome, θ and r values for ‘West’ can be calculated to be, $\theta_2 = 41.7^\circ$ and $r_2 = 10.6$ mm. From equation (4), the ratio of pressures at ‘Center’ (P_{center}) and ‘West’ (P_{west}) is,

$$\frac{P_{center}}{P_{west}} = \frac{\cos(\theta_1)r_2^2}{\cos(\theta_2)r_1^2} = \frac{\cos(0)(10.6)^2}{\cos(41.7)(5.0)^2} = 6$$

The ratio is much higher than the one obtained experimentally i.e. ~ 2 . This could be due to multiple possibilities: i) Theoretically, the dipole should oscillate in one line resulting in the pressure field described by equation 4. However as the rod attached to the sphere is about 18 cm long, the movement of the sphere also has lateral components. This may result in diminished pressures at ‘Center’ and enhanced pressures at ‘West’. ii) Vortices around the oscillating sphere due to the viscous effects may contribute to non-ideal conditions during experiments [7]. For the same reasons four sensors other than Center, which should show similar outputs, are showing variation among them. However, their variation is reasonable considering the fact that output at Center is significantly higher than all of them.

The normalized outputs of sensors 'East', 'West', 'North' and 'South' when each of the sensors was beneath the dipole at a distance of 5 mm, are plotted in a polar plots (a), (b), (c) and (d) respectively, as shown in Figure 3.11. The polar plots demonstrate the directionality of RA dome when placed in a field of oscillating pressure i.e. the sensor which is under dipole shows the maximum output amongst the five sensors. For all the other 4 sensors, both θ and r values are comparatively larger, resulting in reduced pressures at these 4 sensors as compared to the sensor beneath the dipole. This explains the patterns of the outputs at the five sensors and the directionality of RA dome depicted in Figure 3.11. However it can be seen that relative magnitudes of the outputs are not uniform across the 4 plots. This will be discussed later in comparison with simulation results depicted in figure 3.13.

Figure 3.11: Direction detection by RA dome: (a) when 'East' is facing the dipole (b) when 'West' is facing the dipole (c) when 'North' is facing the dipole and (d) when 'South' is facing

the dipole. In each case the distance between the dipole and the dome is 5 mm. The iso-contours represent output voltage (in mV) and the output for ‘Center’ sensor is represented by the blue dot within each quadrangle.

Figure 3.12(a) presents line plots for case when ‘East’ is under dipole and the distance between the dome and the dipole is changed from 5 mm to 30 mm. Throughout the variation of distance, the sensor which faces the dipole (i. e. ‘East’) shows highest output. It is also clear that the device which is on the other side of the dome (i.e. ‘West’) shows the least output for all the distances. From the error bars it can be seen that the outputs of ‘East’ and ‘South’ for distance of 30 mm are distinguishable. However, the trend in the outputs suggests that beyond 30 mm distance they may not remain distinguishable. Figure 3.12(b) shows nonlinear curve fit for the output at East and the output varies with inverse of distance to the power 0.5. This decrease is gradual as compared to theoretically expected trend which should show a decrease inversely proportional to distance squared. This also hints towards the fact that the pressure field generated by the dipole may not be changing as steeply as suggested by theoretical formula.

Figure 3.12: (a) Plot showing variation in output at five sensors with change in distance between dome and dipole when ‘East’ is beneath the dipole (b) Nonlinear fit to the output of ‘East’ sensor.

A simulation is carried out to investigate the variation in pressure distribution on the surface of a dome structure when it is placed at different distances from an oscillating sphere which creates a pressure field. The simulation is conducted using COMSOL's acoustic-structure interaction module in frequency domain. Figure 3.13(a) depicts the geometry constructed for the simulation. A dome of radius 10 mm is placed below the sphere of radius 7.6 mm, at a distance of 5 mm in such a way that 'East' sensor faces the sphere. This assembly is placed in a water tank of dimensions $200\text{ mm} \times 200\text{ mm} \times 200\text{ mm}$. Figure 3.13(b) depicts the pressure field generated by the sphere oscillating at 30 Hz frequency. Figure 3.13(c) depicts a polar plot to compare with polar plot in figure 3.11(a). The ratio of pressures at East to that at West in figure 3.13(a) is 7.3 whereas the ratio of the respective outputs in figure 3.11(a) is 4.9. Figure 3.14(d) shows the variation in the pressure values at sensors 'East', 'Center' 'North' and 'West' when the distance between the dome and dipole is changed from 5 mm to 30 mm. The trends in experimental results shown in figure 3.12(a) are similar to the trends in figure 3.13(c). For example, in both the plots, 'East' shows sharpest drop in output from distance 5 mm to 10 mm. However, in experimental plot in 3.12(a), the output of 'South' sensor should ideally be same as that of 'North', but it isn't. This could be attributed to non-ideal pressure field produced by the oscillating sphere and probable error in alignment of dipole and dome due to parallax.

Figure 3.13: Simulation for RA dome: (a) Geometry used in the simulation: A dome of radius 10 mm is placed beneath an oscillating sphere of radius 7.6 mm. (b) The pressure field generated due to the sphere oscillating at 30 Hz. (c) Polar plot of simulation results for ‘East’ beneath the dipole at 5 mm distance. (d) Variation in the pressure values at devices ‘East’, ‘Center’, ‘West’ and ‘North’ with the distance between dipole and dome.

Overall, the comparison of experimental results of RA dome with analytical and simulated values suggest that the ratios of the outputs of sensors are about 35% of analytical values and about 65% of the simulated results. The non-linear curve fit in figure 3.12 also shows that the decrease in pressure is gradual than what it should be ideally. These comparisons suggest that the pressure field generated by oscillating sphere is diffused in comparison with theoretically

expected fields. As mentioned earlier, this could be owing to the non-ideal oscillations of the dipole sphere and viscous effects that may result in local flows and vortices, making the field non-ideal [7]. However, the proof of concept experiments for RA dome demonstrated that it can be employed for direction detection. For a field that has a profile similar to the ideal one, a dome would show higher directionality.

If RA receptors are compared with canal neuromasts in lateral lines, from the perspective of sensing oscillating signals, there is one significant difference. Lateral lines possess canal structure for filtering out the low frequency noise signals induced by the movement of fish itself [14]; but such a canal structure is non-existent in crocodile ISOs. Though canal structure is absent, the RA receptors in ISOs are associated with lamellated corpuscles which have ability to mechanically filter out the low frequency signals [15]. This facility of mechanical filtering is a desired feature for a mechanoreceptive system and it will be taken up in future.

The pressure distribution on the surface of a swimming fish or a moving AUV is a function of their shape, their orientation with respect to flow and their own movements [16, 17]. There have been attempts of exploiting these dependencies for sensing purpose. Researchers have achieved flow direction detection using pressure sensors mounted on the surface of an AUV e.g. work by Salumae and Kruusmaa [18] and Lagor et al. [19], in which orientation of the pressure sensors was disparate by virtue of the inherent curved surface of the AUV. In such an approach, the pattern in the outputs at different sensors is a function of the surface of the AUV itself. In case of domes mounted on an AUV, the pattern of pressures read by sensors on a dome is also a function of the hemispherical surface of the dome. Since disparate orientations of sensors on a dome are achieved by the dome shape itself, each dome provides directional information. But as these patterns are bound to be influenced by the geometry of surface of the AUV, it would be

interesting to study the correlation between the output patterns on a dome and various factors like curvature of the AUV, position of the dome on the surface of the AUV and orientation of AUV with respect to flow. The fact that each dome shaped receptor provides directional information implies that if there are smaller streams imparting pressure only on a small section of an AUV, SA domes in the section can provide information about speed and direction of the stream. This could also be advantageous in detecting local flow variations created due to movements of small objects and animals.

Before discerning information about direction and speed of the flow from a pattern of sensor outputs on a dome, the position of each sensor is known to the system. The sensor that shows the maximum output provides information about the direction of flow. Since the sensor is facing the flow, the magnitude of its output would give information about the velocity of the flow. In other words, the pattern of outputs of sensors provides information about the direction and information about velocity can be obtained from the magnitude of one sensor that faces the flow. To discern complex situations, advanced data processing algorithms and machine learning techniques will be needed. For example, a system with supervised machine learning, after a comprehensive training data about the patterns of outputs for various known stimuli/situations, will be able to retrieve the information about speed and direction of an unknown stimulus.

3.6 Sea trials

The proof of concept experiments conducted on artificial SA and RA domes are performed in controlled laboratory environments. The results from these experiments demonstrate that these domes can be employed for direction detection and flow sensing applications. However, the applicability of ISO-inspired domes in real life scenario is yet to be explored. With objective of

exploring the viability of the dome shaped sensor in relatively hostile sea environment, sea trials are conducted. In these experiments, SA domes mounted on an autonomously controlled kayak are tested for direction detection and flow sensing ability.

3.6.1 Preparation and experiments

A hollow dome with five slots to mount pressure sensors, is 3D printed. The outer radius of the dome is 10 mm and the dimensions of each of the rectangular slots are 5 mm $\times$ 3.5 mm. Two through holes are provided for each slot for passing the connecting wires (Figure 3.14(b)). Five piezoresistive pressure sensors (Figure 3.14(a)) with LCP membrane and gold strain gauges are placed in the slots (Figure 3.14(c)). Four sensors are at 45° latitude and one sensor is at the apex of the dome. Contact pads of each sensor are connected with the wires using conductive epoxy - EPO TEK H20E (Epoxy Technology Inc.). The dome is filled with PDMS and cured for 2 hours at 75°C. PDMS would support the wires and prevent them from being in contact with the neighboring wires. A layer of Sil-poxy (Smooth-On Inc.) is applied on sensing membranes for protection and insulation of the strain gauges. Sil-poxy is very soft and stretchable (elongation at break being 750%) material. It is applied on the diaphragm by dispensing a limited quantity using a needle and is cured at room temperature. Calibration of sensors is carried out after Sil-poxy is coated on the diaphragm. This protective layer is critical from the perspective of insulation of the sensors from sea water. The dome is then placed on a PDMS support slab so that it can be mounted on a kayak. Figure 3.14(d) shows a dome mounted on the kayak in such a way that 'East' sensor is towards the front end of the kayak and 'West' sensor is towards the rear end.

Figure 3.14: (a) Photograph of piezoresistive, LCP pressure sensor (b) Image of 3D printed dome with sockets for placement of the LCP pressure sensors. (c) An SA dome with LCP piezoresistive pressure sensors mounted on it. (d) An SA dome mounted on the sidewall of the front end of kayak. ‘East’ sensor faces the front end whereas ‘West’ sensor faces the rear end of the kayak.

Each sensor is connected to a Wheatstone’s bridge circuit and is biased with 5 V constant voltage source. When a flow imparts pressure on diaphragm of the sensor, the diaphragm bends; resulting in a change of resistance of the strain gauge. The change in the resistance is converted into voltage through the Wheatstone’s bridge network. The circuits are placed in the kayak along with the constant voltage source and data acquisition card (NI-DAQ USB-6128). Figure 3.15 shows a representation of control scheme employed during the sea trial experiments. Two computers in a control room are utilized to achieve real time control and data acquisition. The control room is situated on a barge from which the kayak is deployed. One computer is used for real time autonomous control of the kayak and the other one is used to record the data by remotely accessing an on-board computer housed in the kayak. SA dome mounted on the kayak has five LCP pressure sensors which sense the variation in pressure due to the movements of the

kayak. The sensor outputs are collected by the on-board computer through Wheatstone's bridge circuits and data acquisition card placed inside the kayak.

Figure 3.15: Diagram depicting the control scheme employed during sea trials: A computer is used to autonomously control the movements of kayak and another computer is used to record the data from an on-board computer.

3.6.2 Experimental results

The experiments are carried out to explore the ability of the dome to detect the direction of relative movement between flow and the kayak. At first the kayak is held steady in stream and then released to drift along with the stream. Figure 3.16 shows how the outputs of four sensors, 'East', 'West', 'North' and 'South' change during this process. 'East' being the sensor facing the incoming stream, shows the highest decrease amongst the sensors, on releasing of the kayak.

‘North’ and ‘South’ show unequal change in the outputs. This could be attributed to the fact that they are not in identical positions as in case of lab experiments. ‘South’ sensor is towards the surface of water whereas ‘North’ is away from the surface.

Figure 3.16: Outputs of sensors ‘East’, ‘West’, ‘North’ and ‘South’ when kayak is held in the stream and then is released to drift along with the flow. ‘East’ sensor being the one facing the flow shows the maximum reduction in the output.

In the next set of experiment the kayak is made to move upstream and downstream with same speed and the outputs of the four sensors are recorded. Figure 3.17 shows polar plots for the upstream and downstream movements. As the drag force is more when the kayak moves upstream, the output at all four sensors is higher as compared to that when kayak moves downstream. In both cases the ‘East’ which faces the flow shows the highest output and the ‘West’ shows the least output, demonstrating the directionality of the dome.

Figure 3.17: Polar plots depicting the outputs of the sensors when kayak moves upstream and downstream.

Overall, in the sea trial results, ratio of output at East and West is higher than that of North and South. However as compared to lab experiments, the directionality is reduced due to the fact that the flow is not as controlled and uniform as in the case of lab experiments. Low output levels during sea trials could be attributed to thick silpoxy layers applied on the sensors to protect them from harsh sea water.

Previously the ISO-inspired SA domes have been tested successfully in lab environment. The sea trial results are encouraging since they provide testimony to the fact that SA domes are capable of providing hydrodynamic information in real and harsh sea environment as well. The results obtained are qualitative in nature and this work can be advanced by carrying out experiments for

quantitative analysis of the performance of the dome sensors for real time experiments in harsh environment.

3.7 Conclusions

ISOs in crocodiles can be an inspiration for developing an underwater passive mechanoreception system for AUVs to be aware about their surroundings by gathering cues from the flows and disturbances around them. Drawing inspiration from SA and RA receptors associated with dome shaped ISOs, artificial SA and RA domes are fabricated using piezoresistive and piezoelectric pressure sensors respectively and tested for their direction detection ability. The experimental results demonstrate that with the proposed SA dome structures, direction and magnitude of steady flows can be detected from the output pattern of sensors placed on the dome surface. Whereas the proposed RA dome structure can be employed to detect the position of source of oscillatory disturbance. The applicability of SA dome to underwater sensing for a moving AUV is demonstrated through experiments conducted by mounting SA dome on a kayak. The viability of SA domes is also explored and demonstrated through the sea trial experiments.

The sensors on a moving AUV would experience static pressure due to depth and dynamic pressures due to flows. For sensing system to be aware of flows, it is critical to offset the static pressure due to depth. An independent depth sensor can be incorporated into the system to measure the static pressure and the depth information can then be utilized to calibrate/adjust the response of the sensors to reflect only the information about flows. Considering the fact that each SA and RA dome can provide information about both direction and magnitude of flows and oscillating disturbances respectively, a set of SA and RA domes strategically mounted on surface

of an AUV can be a good prospect for an AUV to be cognizant of all the flows and obstacles in its vicinity, thereby making its control and maneuvering more energy efficient.

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4

OBJECT DETECTION EXPERIMENTS

This chapter starts with brief introduction to various aspects associated with underwater hydrodynamic object detection. It then proceeds to describe the object detection experiments conducted with SA dome and discusses the results.

4.1 Introduction

A passive hydrodynamic sensing system gathers information through the changes in flows and pressures that it can measure. The stimuli are essentially of mechanical nature and can be classified in two categories. The first category of stimuli is associated with flow – velocity of the flow, drag force imparted by the flow and pressure variations caused by hydrodynamic phenomena like vortices. The information about flows is useful in identifying speeds and directions and can be employed for achieving energy efficient maneuvering. The experiments described in previous chapter are related to investigation of ability of domes in determining flow velocity and direction of flow. The stimuli of second category are generated by the movements of objects in the proximity of the system. Information about objects is useful in being aware about movements and identifying the characteristics like size, distance and speed of the object. This chapter is dedicated to exploring the ability of an SA dome to discern the stimulus generated by an object moving at different speeds and distances from the dome.

4.2 Object detection and hydrodynamic passive sensing

For any AUV, it is indeed important to be aware about the movements of objects or animals in its vicinity. There are several ways to obtain this information. It can be obtained optically, acoustically or hydro-dynamically. There are pros and cons of each of these methods. Optical and acoustic methods may provide data for greater distances but they may not be effective in dark, turbid and cluttered waters. On the other hand, hydrodynamic method works only for short distances – typically a few times the length of the sensing array [1]. However, it can function in dark and turbid waters. Any movement in water is bound to produce hydrodynamic signals and

therefore ability to detect and interpret hydrodynamic stimuli is a great value addition to sensing capabilities of an AUV.

It is a challenging task to correlate a received hydrodynamic signal with movement of an object which generated it. There have been several efforts in this regard in last two decades and they can broadly be classified into three categories. The first category of research employs lateral line-inspired arrays and aims at interpreting the hydrodynamic patterns generated due to linear movement of an object [2, 3]. The second category of research targets localization of an oscillating dipole using lateral line-inspired array of flow sensors [4-6]. The third category of research is inspired from harbor seal whiskers and tries to study the wake caused due to passing of an object or wake behind a stationary object placed in a flow [7, 8]. With an ISO-inspired dome, the first step in regards to object detection experiments would be to explore the output patterns across the sensors on the dome when an object is towed in its vicinity.

4.3 Object detection experiments

The process of object detection is about identifying and matching patterns of responses of sensing system with patterns of stimuli. The object detection task can be divided into two different problems – i) forward problem: given the parameters of the movement of the object (direction, speed and distance), identify the pattern of the outputs of the sensor array. ii) Inverse problem: Given the pattern of the outputs of the sensor array, determine the parameters of the movement.

So, the first step is to solve the forward problem by exploring and identifying the output patterns for known set of stimuli. In past, there have been various studies on different aspects of object detection and identification through a linear array of sensors. Their objectives span from finding position of the object [2] to more complex problem of identifying the shape of the object [3].

However, there aren't many studies on hydrodynamic object detection using hemispherical array of sensors. Considering that this attempt includes a hemispherical array, the focus for this study is to investigate output patterns for movements of an object. The work described in this chapter is focused on solving the forward problem and the experiments are designed accordingly.

4.3.1 Parameters under consideration

The object detection experiments aim at investigating variation in output patterns on ISO-inspired dome, with respect to various parameters associated with the movement of an object. The cues about these parameters could be provided by the pattern of magnitudes of sensors' outputs on the dome or by variation in the outputs over a period of time.

For such experiments the first critical choice to be made is the object itself. The object selected for these experiments is a cylindrical rod with a circular cross section, considering the fact that it is the lowest order shape. As the complexity of shape increases (eg. a rod with square cross section), perturbations that it causes in potential flow also increase [2]. Moreover, pressure variations caused by movement of a rod is a complex problem in fluid dynamics and potential flow model provides a simplified prediction of pressure for cylindrical rod as,

$$P = U^2 C(x, r, \rho) \quad \text{..... (4.1)}$$

where, U is the velocity of the cylinder, x is the position of the center of the cylinder, r is the radius of the cylinder and ρ is density of water. Though it is not an adequate model, it does give a reference for comparison of obtained trends in outputs [2]. In other words, a cylindrical rod would be an apt starting point for object detection experiments before delving into more complex shapes.

As the main objective is to obtain information about the movement of an object, there are three parameters under consideration.

i) Distance at which the movement occurs: One of the critical information about an object in the vicinity of an AUV would be answer to question ‘how far is the object?’ Ideally a hydrodynamic sensing system should be able to locate the position of an object in three dimensions. However, a simpler case of movement in two dimensions is considered in this work, factoring in two axes – a) axis along which rod is moved in a straight line b) axis perpendicular to the line of movement and parallel to dome base as shown in figure 4.1. As the rod moves along the line of movement, its distance from dome is constantly changing. The distance of closest approach of the path (indicated by red arrow in figure 4.1) is considered as a parameter of the movement. Sensor output could provide indication of the distance as the pressure impulse generated by the movement of a rod decays with distance square [9].

Figure 4.1: A schematic showing the top view of the rod and dome to depict the directions and axes system.

ii) Speed of the movement: Speed is a crucial aspect of state of motion of an object. There are two aspects related to the speed of an object moving through a fluid that are important from object detection perspective. Firstly, pressure due to movement of a cylindrical rod can be approximately modeled through potential flow model. In potential flow models, a potential function can be defined assuming incompressible, inviscid and irrotational flow. Secondly, from

the potential function, velocity vector can be obtained which then can be correlated to pressure through Bernoulli's equation. For example, one of the potential flow models that can be used to model cylinder is known as Rankine half-body. A complex potential function obtained through this model is given by [10],

$$\phi(z) = u(z + a \log(z - z_0)) \quad \dots\dots (4.2)$$

where, z_0 is center of cylinder and a is radius of cylinder.

The potential function then can be input in unsteady Bernoulli equation to obtain pressure field [10].

$$P(z) + \frac{1}{2}\rho \left| \frac{\partial \phi(z)}{\partial z} \right|^2 + \rho \frac{\partial \phi(x,y)}{\partial t} = P_\infty + \frac{1}{2}\rho u_\infty^2 \quad \dots\dots (4.3)$$

Where, P is pressure, ρ is density of water and u is speed of the flow. Subscript ∞ refers to free stream pressure and flow speed.

Though in this work the potential flow models are not dealt with in detail, we will be referring to a result of potential flow model, i.e. the pressure due to a moving rod is proportional to square of its speed [2].

iii) Direction of the movement: Identifying the direction of movement is also critical. It is expected that the directionality of dome would play an important role in this. The pattern of the outputs of sensors across the dome will be significantly altered for flows from different directions due to spatial filtering that a hemisphere offers.

Acceleration is a parameter associated with motion of an object, which is not considered as a parameter in this study. A rod accelerated through water is a more complex case from fluid dynamics perspective due to vibrations and disturbances it generates. In fact, during the experiment it is important to minimize the effect of acceleration of rod, so that the pressure stimulus generated due to moving rod is free of perturbations [10]. It is done by starting and

stopping the movement of rod at a distance of 2 m from the dome, so that the effects of sudden starting and stopping of rod are kept to a minimal.

So, to summarize, the objective of these experiments is to investigate the ability of ISO-inspired domes to detect the direction of the movement of an object, distance at which the movement occurs and speed of the movement. For object detection experiments, it is crucial to have an experimental setup in which the movement of the object is precisely controlled. Considering the possibility of feeble signals for low speeds and greater distances, it is equally important to have circuits and data acquisition system that is capable of minimizing the noise and amplifying the signals.

4.3.2 Fabrication and packaging of SA dome

A hollow dome of radius 2 cm is fabricated using 3D printing technology. The dome is designed to have 5 slots of dimensions 6 mm $\times$ 4 mm for placement of piezoresistive pressure sensors (Figure 4.2(a)). Each slot is provided with two through-holes for passing the connecting wires for each sensor. After passing connecting wires through the holes, the dome is filled with polydimethylsiloxane (PDMS) and cured for 2 hours at 75°C, to support the connecting wires. Five piezoresistive pressure sensors are mounted on the five slots on the dome (Figure 4.2(b)). The five sensors are labeled as ‘Center’, ‘East’, ‘West’, ‘North’ and ‘South’. The contact pads of the sensors are connected with wires using conductive epoxy - EPOTEK H20E (Epoxy Technology Inc.). To minimize the noise, shielded wires are used.

Figure 4.2: (a) Photograph of the pressure sensor with gold piezoresistor patterned on a liquid crystal polymer membrane. (b) Image of an SA dome constructed by mounting five piezoresistive pressure sensors on a 3D printed dome. The contacts of the sensors are connected to shielded wires passing through the dome.

4.3.3 Circuits for improved data acquisition

Apart from possibility of signal being weak, another concern is the presence of noise. The noise is primarily of two types. First and the strongest component of noise originates from the gantry motor and the second component is electronic noise. It is imperative to include a filter circuit for noise removal and an amplifier circuit for amplification of the signal, in the data acquisition system. Figure 4.3 depicts the building blocks of the data acquisition system. Each sensor is connected to a Wheatstone's bridge and output of each Wheatstone's bridge goes as input to a filter-amplifier circuit. The output of the amplifier circuit is read through DAQ USB-6210 and recorded using LABVIEW.

Figure 4.3: Building blocks of the data acquisition system used for object detection experiments.

Wheatstone's bridge circuit and filter-amplifier circuits are depicted in figures 4.4(a) and 4.4(b), respectively. The sensors on the dome are piezoresistive, and therefore each of the sensors needs to be part of a Wheatstone bridge circuit so that the change in resistance can be recorded in terms of voltage. In the Wheatstone's bridge, three resistors are chosen to be same ($120\ \Omega$) and the fourth resistor is the piezoresistive sensor on the dome. Five Wheatstone's bridge circuits share a common DC power supply of 5V.

A third order RC low pass filter circuit is designed to have a cut-off frequency of 70 Hz by using a resistor of $23\ \text{K}\Omega$ and a capacitor of $0.1\ \mu\text{F}$. The objective of this circuit is to filter out higher frequency noise caused by the motor of the gantry. For amplifying the signal, instrumentation amplifier AD620AN is used. The resistor connected between pins 1 and 8 determines the gain and with a $4.7\ \text{K}\Omega$ resistor, it is set to be 10.4. Each filter-amplifier is provided with an independent 12 V dual power supply.

Figure 4.4: Circuit diagrams: (a) Wheatstone's bridge circuit and (b) filter and amplifier circuit. For simplicity of diagram, first order RC filter is shown. However a third order RC filter is used in experiment with R and C values as mentioned in the diagram.

Figure 4.5: A photograph of printed circuit board containing five Wheatstone's bridge and five filter- amplifier circuits.

Figure 4.5 shows the printed circuit board that is used during object detection experiments. It comprises Wheatstone's bridge circuits which incorporate inputs from sensors. The outputs of Wheatstone's bridges are fed to filter amplifier circuits and the outputs of amplifiers are connected to DAQ.

4.3.4 Experimental set-up

The experiments to investigate object detection ability of the ISO-inspired dome shaped sensor are carried out in a tank. The dome is mounted on a support slab attached to wall of the water tank. A cylindrical rod of diameter 32 mm is attached to a gantry. The experimental arrangement is shown in Figure 4.6(a). The gantry can be towed at desired speeds and direction by using software called PEWIN32PRO2. The movement of the rod and recording of the data is synchronized through a custom designed user interface in LABVIEW. The synchronization would help in correlating the outputs of the sensors with the movements.

Figure 4.6: (a) SA dome placed on a support slab inside a towing tank. A rod attached to a gantry can be towed at desired speeds and directions.

Three sets of experiments are carried out to explore the effect of these parameters. Figure 4.7 depicts the movements of rod (denoted by brown circle) in the three sets. In Set 1, as shown in Figure 4.7(a), the rod is moved inline (denoted by black arrow) to the dome (denoted by yellow circle) and is stopped at a particular distance (denoted by red arrow) from the dome. Figure 4.7(b) depicts Set 2, which in a way is an extension of Set 1. The rod is moved in straight line and stopped at a distance. Same movement is repeated for various lateral distances denoted by the red arrow. The lateral distance is the parameter that is varied in this set. In set 3 (Figure 4.7(c)), the rod is moved in a straight line and passed by dome at a particular distance (denoted by red arrow) from the dome. The starting point and the end-point of the linear movement are equidistant from dome.

Figure 4.7: Schematic representation movements in each of the sets of experiments: (a) Set 1 with inline movement (b) Set 2 with variation in lateral distance (c) Set 3 where rod is passed by the dome. In each case the black arrow denotes the path of the movement of rod and the red arrow denotes the distance parameter.

4.4 Results and discussions

The collected data is analyzed to examine how the outputs of the five sensors reflect the movement of the rod and how the outputs vary with the change in distance and speed of towing. The imperfections or dissimilarities in fabrication and packaging processes may result in differences in responses of the 5 sensors to the same stimulus. A calibration process is carried out to bring parity amongst the five sensors on a dome for analysis.

4.4.1 Set 1 - Inline movement

As mentioned earlier, experiments in Set 1 involve moving the rod along a linear path denoted by yellow arrow and stopping at a distance denoted by red arrow in Figure 4.8. The rod is towed towards ‘South’ sensor as shown in Figure 4.8 and equal number of runs is executed for movement towards ‘North’ sensor. Variation in direction is binary i.e. only directions opposite to

each other (north to south and south to north) are tested. The speed is varied from 0.1 to 1 m/s and the distance is varied from 2 to 10 cm.

Figure 4.8: Top view of the experimental set-up in Set 1, with ‘North’ (N) and ‘South’ (S) sensors labeled. The yellow arrow denotes the line along which a rod is towed and it is stopped at a distance denoted by the red arrow. The movements executed in this set are towards ‘South’ and ‘North’ sensors.

4.4.1.1 Directionality of the dome based on magnitude of outputs

When the towed rod is brought to rest at a particular distance, a pulse is generated in water which travels towards the dome. Each of the sensors on the dome experiences an increased pressure due to the pulse. The output of each sensor shows a corresponding increment. The polar plots in Figure 4.9 show the magnitudes of the increments for each sensor in the situation where towing speed is 0.2 m/s and distance is 2 cm. Figure 4.9(a) depicts the outputs when the rod movement occurs on north side and Figure 4.9(b) shows the case when the movement is on south side. From the polar plot, it is evident that the sensors ‘North’ and ‘South’ show highest outputs for the

respective cases. The output at ‘North’ in 4.9(a) and that of ‘South’ in 4.9(b) are not equal. Similarly, the outputs of ‘East’ and ‘West’, which should be equal, show variations. The discrepancies could be due to disturbances that are created after the rod stops. Also the Reynolds number for the movement is 6400, which could have turbulent component. However, despite the discrepancies, the polar plots suggest that the dome can indicate the direction at which the movement occurs.

Figure 4.9: Directionality of SA dome: Polar plots depicting the outputs of the sensors when rod moves towards (a) North and (b) South sensors at a speed of 0.2 m/s and stops at a distance of 2 cm. The values denoted in the plots are averages taken over five runs.

4.4.1.2 Directionality of the dome based on patterns in outputs

A cue about the direction of the stimulus can also be obtained from observing how output of individual sensors change when the stimulus reaches the dome. Figure 4.10 shows filtered raw outputs of ‘North’ and ‘South’ sensors after calibrating for the offset of the baseline, when rod is made to move towards the dome at a speed of 0.6 m/s and stopped at a distance of 2 cm on north side. The output of ‘North’ increases from the base level; however in case of ‘South’, there is a dip (indicated by dotted red ellipse in figure 4.10(b)) in the output before the rise. Since the

stimulus is coming from north side, the ‘South’ sensor lies in the wake region formed due to flow separation and therefore it would experience a decrease in pressure. This pattern of decrease in the output can also be used to indicate the direction of the movement of the rod.

Figure 4.10: Outputs of (a) ‘North’ and (b) ‘South’ sensor, when the rod movement occurs on north side at a speed of 0.6 m/s and stops at a distance of 2 cm.

4.4.1.3 Variation in output with distance and towing speed

The variation in output of a sensor with change in distance and speed of towing is also investigated. Figure 4.11(a) shows how output of ‘North’ sensor changes when the rod is towed at a speed of 0.1 m/s and made to stop at distances of 2, 4, 6, 8 and 10 cm on north side of the dome. As the rod stops farther from dome, the magnitude of the stimulus reaching the dome diminishes and so does the output of ‘North’ sensor. In general, the output voltage decreases with distance. However, there is not a significant difference between the consecutive data points. This implies that though the prediction of the distance at which an unknown object stops, based on the stimuli it generates can be ball parked within a range, it cannot be accurately predicted. Figure 4.11(b) depicts output of ‘North’ sensor when the rod is towed at speeds of 0.1, 0.2, 0.4, 0.6, 0.8 and 1.0 m/s and brought to rest at a distance of 6 cm. The output shows increments with

increase in the speed. However, it reaches saturation at higher speeds, indicating that the directionality of the dome may be reduced at higher speeds.

Figure 4.11: (a) Variation in output of 'North' sensor with distance, for the cases when the rod is moved on north side at speed 0.1 m/s. (b) Variation in output of 'North' sensor with towing speed, for the cases when the movement occurs on north side at a distance of 6 cm. In both the plots means of five runs are presented and standard deviation is represented by the error bars.

Pressure pulse caused by a moving rod is proportional to square of the speed of the rod. However, in the case where the rod moves in line and comes to a halt, along with the pressure pulse, water dragged with rod also adds to the stimulus. The combined stimulus results in a step-like response from sensor as shown in figure 4.10. Therefore the results in figure 4.11 are not compared with theoretical dependence of the output on respective variables – distance and speed. The dependence is relevant for the case where rod passes by the dome and is discussed in section 4.4.3. Also, after the rod stops, it disturbs the water that was dragged by the rod itself. This could be a probable reason behind the taller error bars in figure 4.11. However the results in figure 4.11 do demonstrate that SA dome can discern the information about distance and speed of the movement of an object moving in line with the dome and stopping at a distance.

4.4.2 Set 2 - Variation with lateral distance

The most interesting observation from Set 1-experiments is the decrease in pressure sensed by the sensor on the side opposite to the movement. Set 1 experiments consist the simplest case that combines inline motion and stopping of the rod at a distance from dome. Set 2 experiments are extension of Set 1 experiments, where the movement is same but the line of movement is shifted laterally away from dome. These experiments are aimed at exploring how the feature of dip in pressure varies across the sensors on dome as the line of movement becomes increasingly off from the inline movement in Set 1. In Figure 4.12, the dotted yellow arrow denotes the path used in Set 1 and solid yellow arrows denote the paths of the movement in Set 2. The heads of the solid yellow arrows indicate the positions where the rod stops and the red arrow denotes the lateral distance that is varied in these experiments. Observations are recorded for distances of 1, 2, 4 and 6 cm and for speed of 0.2 m/s.

Figure 4.12: Top view of the experimental set-up in Set 2. The movements executed are in straight line denoted by solid yellow arrows at a lateral distance denoted by red arrow.

4.4.2.1 Observations about dip in output

As mentioned earlier, Set 2 experiment is to explore how movement of rod at varied lateral distances, affects the pattern of the dip in output of the sensors. Amongst all the sensors on the dome, only ‘East’ sensor is observed to be manifesting the effect of variation in lateral distance, in terms of change in ‘dip in output’ pattern. Figure 4.13 shows filtered raw outputs of ‘East’ sensor, for rod towed at speed 0.2 m/s at lateral distances of 1, 2, 4 and 6 cm on north side of the dome. Each individual plot shows output of the sensor over a period of about 20 seconds. Each plot shows broadly same trend - a low level of output up to about 10 seconds and then a rise to a higher level. The rise in the output is caused by the water moved towards the dome due to stopping of the rod at a particular lateral distance.

As the lateral distance of the path of the rod increases, the angle at which the stimulus reaches the dome also increases. For paths at distances 1, 2 and 4 cm, ‘East’ sensor doesn’t exhibit any dip before rise of the output to higher level. However, at distance 6 cm, it shows a dip, indicating that it falls within the wake region. The occurrence of the dip is a consistent observation, and this demonstrates that linear movements at different lateral distances can also be discerned through the temporal patterns of the sensor outputs. Dip in output at ‘East’ is also observed when a rod passes by the dome on west side and it is discussed in section 4.4.3.3.

Figure 4.13: Output of 'East' sensor for rod moved at speed 0.2 m/s towards 'South' sensor at lateral distances (denoted by red arrows) of 1, 2, 4 and 6 cm. The dip in output of 'East' for lateral distance of 6 cm, is marked with red dotted ellipse.

4.4.3 Set 3 - Passing by dome

First two sets of experiments involved stopping of a moving rod, at a distance from dome. These sets are more of exploratory nature to see what kind of patterns to expect from the sensors on dome. The third set of experiments involves a rod passing by the dome at a particular distance and is a more realistic scenario. Figure 4.14 depicts the path along which the rod is moved, by yellow arrow. The path is symmetric about dome position, i.e. the starting and stopping points of the rod are both at a distance of 2 m from the dome. The rod is towed at a distance (denoted by red arrow in Figure 4.14) of 6 cm from the dome. The rod is moved at speed of 0.2 m/s, for two directions - north to south and south to north.

Figure 4.14: Top view of the experimental set-up in Set 3. The movement of the rod is along the solid yellow arrow which is at a distance, denoted by red arrow, from the dome.

4.4.3.1 Directionality of the dome based on magnitude of outputs

When the rod moves past the dome from south to north direction, the movement causes changes in the outputs of each sensor on the dome. Figure 4.15 depicts filtered raw outputs of ‘East’, ‘West’, ‘North’ and ‘South’ over a period of 30 seconds, for a single run when rod moves from ‘South’ to ‘North’ passing by the dome at a distance of 6 cm on west side. The rod passes by the dome at around 13 s mark and the movement is reflected in the outputs in the form of peaks highlighted by dotted red ellipses in figure 4.15. The height of the peak can be measured from the baseline (output before the arrival of the rod) of the respective sensor and the peak at ‘West’ sensor is the tallest of all the four sensors.

At a later instance, water that dragged along due to the movement of the rod makes the outputs of all the sensors to increase (highlighted by dotted green ellipses in figure 4.15). ‘South’ sensor faces this inflow of water and therefore the output of ‘South’ rises above the rest. As ‘North’

sensor lies on the opposite side it shows a lesser increase. As the path of the movement lies on the west side of the dome, ‘West’ sensor is exposed to the stimulus more than ‘East’ sensor.

Figure 4.15: Outputs of four sensors – ‘East’, ‘West’, ‘North’ and ‘South’ when the rod is towed from south to north, passing by the dome at a distance of 6 cm and at a speed of 0.2 m/s.

In other words, immediately after the rod passes by at about 13 s mark, ‘West’ shows the highest output and then after 20 s mark, ‘South’ shows the highest output amongst the four sensors. The polar plots in figure 4.16 reflect the two aforementioned observations regarding the outputs. The values represented in the polar plots in figure 4.16 are averages of calibrated outputs taken over five runs. Figure 4.16(a) is associated with the observation that is highlighted by dotted red ellipses, whereas figure 4.16(b) is associated with that highlighted by dotted green ellipses.

Figure 4.16: Polar plots showing magnitudes of outputs of four sensors – ‘East’, ‘West’, ‘North’ and ‘South’ when the rod is towed from south to north at a distance of 6 cm and at a speed of 0.2 m/s. (a) Output values of the peaks immediately after the rod passes by the dome at 13 s mark. (b) Output values after 20 s mark. All the values in the polar plots are averages taken over 5 runs.

For speed 0.6 m/s, the peak highlighted by the red ellipse doesn’t remain distinct from the region highlighted in the green ellipse. The difference between the outputs at ‘West’ and ‘South’ becomes insignificant - West (Mean = 0.080, SD = 0.008), and South (Mean = 0.073, SD = 0.005), conditions; ($t(4) = 2.42, p > 0.05$). For speed 0.8 m/s as well, the difference is found to be insignificant. This implies that for speeds greater than or equal to 0.6 m/s, it is hard to predict the direction based on the outputs.

The peaks highlighted by red ellipses in figure 4.15 are due to the pulse generated when the rod passes the dome. The variation of amplitude of the peak with speed and with distance is depicted in figure 4.17(a) and 4.17(b) respectively. Pressure generated by a moving cylindrical rod can be modeled through a potential flow model of a circular cylinder in steady flow. The pressure is given by,

$$P = U^2 C(x, r, \rho) \quad \dots\dots (4.4)$$

where, U is the velocity of the cylinder, x is the position of the center of the cylinder, r is the radius of the cylinder and ρ is density of water. Though the graph in figure 4.17(a) shows increase in output with increase in speed, it doesn't show a square law dependence of output on the speed. The variation in pressure with respect to distance can be approximated to inverse square law [9]. However the graph in 4.17(b) depicts a more gradual decrease with $1/\text{distance}$ rather than inverse square of distance.

The deviations of the plots in 4.17(a) and 4.17(b) from their respective expected behaviors could be due to the following two reasons. Firstly, this could be owing to the fact that the potential flow model that predicts the U^2 dependence, doesn't take into account the wake region [2, 9]. Also, the model assumes ideal conditions like irrotational fluid. In the real case scenario, there is a wake region as the rod passes by the dome and the fluid is not irrotational. Secondly, the velocities from 0.4 m/s to 1 m/s correspond to Reynolds numbers of 12800 to 32000, which may result in turbulent movements of water causing pressure variations that are not anticipated. The aforementioned reasons may lead to outcomes that are different than the theoretically expected ones. Though the trends in figures 4.17(a) and 4.17(b) are not exactly similar to the theoretically expected ones, they do provide a template which can help identify the distance and speed of an unknown object passing by.

Figure 4.17: (a) Variation in output of 'South' sensor with towing speed, when the rod passes by the dome a distance of 6 cm. (b) Variation in output of 'West' sensor with distance, for the cases when the rod passes by at distances at speed 0.2 m/s. In both the plots means of five runs are presented and standard deviation is represented by the error bars.

4.4.3.2 Directionality of the dome based on time lag between first peaks

Apart from magnitudes of the outputs, the positions of the peaks (highlighted with red ellipses in figure 4.15) on the timeline can also give cues about the direction of movement. As the rod passes by the dome on west side, from south to north, 'South' receives the stimulus followed by 'West' and 'North'. The distance between the 'North' and 'South' sensors is 28 mm and time taken by rod to cross 28 mm at speed 0.2 m/s is 0.14 s. However, there is additional time needed for the stimulus to reach the sensors. For rod passing at speed of 0.2 m/s, the difference between the time positions of the peaks at 'South' (T_s) and 'North' (T_n) is observed to be 0.6 s. Also, stimulus reaches 'West' first and then to 'East' with difference ($T_e - T_w$) being similar in magnitude to the ($T_n - T_s$). In fact, for movement of rod from south to north, consistently the sequence of first peaks on the time line is observed to be $T_s < T_w < T_n < T_e$.

A paired t-test is conducted to check the significance of the difference for a data set of 5 runs.

The difference between T_s and T_n is found to be significant - T_s (Mean = 12.35 s, SD = 0.057 s)

and T_n (Mean = 12.98 s, SD = 0.1 s), conditions; $t(4) = 12.21$, $p < 0.01$. Similarly, $(T_s - T_n)$ for rod movements at speeds 0.1 m/s and 0.4 m/s is found to be 1.3 s and 0.17 s respectively. In both cases the difference is statistically significant ($p < 0.01$).

Figure 4.18: Schematic representation of top view of the dome and rod system with its measurements.

The time lag between the peaks at ‘North’ and ‘South’ provides information about speed and direction of the movement. However for speed 0.6 m/s, $(T_s - T_n)$ is found to be statistically insignificant ($p > 0.05$). This implies that for the dome, cues about direction of movement can be obtained through time positions of the peaks only up to speeds of 0.4 m/s. For linear arrays, similar information is obtained through time lag in the peaks at multiple sensors along the length of the array [9, 10]. However the information can only be in one dimension. On the other hand, for a dome shaped array, time lag is there in both – north-south and east-west directions, and therefore information can be obtained in two dimensions.

4.4.3.3 Directionality of the dome based on pattern of dips

Figure 4.19 depicts filtered raw outputs of four sensors for rod movements in two opposite directions. For north to south movement of rod at a distance of 6 cm, sensors ‘East’ and ‘South’ lie on the side opposite to the arrival of stimulus. On the other hand, for south to north

movement, sensors ‘East’ and ‘North’ lie on the side opposite to stimulus. This is reflected in form of dips in the outputs of these sensors just before the rise of the output levels of respective sensors. These dips are shown by red ellipses in Figure 4.19. ‘East’ shows a dip for movement in both the directions since the path of the movement lies on west side. ‘North’ and ‘South’ show dip only when the rod approaches the dome from opposite side. This pattern of dips can also provide hints about the direction of movement. A linear array of sensor would provide information about an object passed by it, in form of – i) pattern of magnitudes of outputs of sensors and ii) time delays between the peaks at each sensor [9, 10]. However a linear array cannot provide additional information like the dips in the outputs of certain sensors based on the direction of stimuli. In case of dome shaped array, the hemispherical shape itself facilitates spatial filtering when stimulus arrives and causes sensors on the opposite side respond differently in form of a dip in output. So, the information in form of dips is obtained by virtue of the dome and it is peculiar to dome shaped array. Considering that the dips have been present in all the sets of experiments, it would be interesting to investigate the dips in detail from a fluid dynamics perspective. Visualization of flow around the dome when a rod passes by it, using a technique like particle image velocimetry will help in understanding how exactly the water moves close to the surface of dome. A further investigation on the dip can be undertaken through numerically intensive simulation [2] that takes into account the fluid structure interaction during movement of the cylinder and predicts pressure variations generated by it. Alternatively, an analytical approach can be taken by obtaining flow potentials of cylinder movement [11] and then calculating pressure values in three dimensional space by taking the presence of dome into account. This kind of investigation lies outside the scope of this work.

Figure 4.19: The dips in the outputs of the sensors: For north to south movement, ‘East’ and ‘South’ show dips and for south to north movement, ‘East’ and ‘North’ show dips.

4.5 Conclusions

An ISO-inspired dome is constructed and its ability to obtain information about movement of an object in its close proximity is investigated. The outputs of the sensors can be analyzed to obtain information about the speed of the object and the distance at which the movement occurs. However, the cues about the direction of the stimulus can be provided by both, magnitudes of outputs of five sensors and temporal pattern of outputs of individual sensors. The experimental results of the study are encouraging and based on the results, it can be concluded that dome shaped sensor is capable of discerning the information about movement of an object in its vicinity. An algorithm that takes into account the patterns in magnitudes of the outputs peaks, specific temporal patterns like dips in outputs, and cues about time differences between arrivals of signals at different sensors, can be developed and employed to obtain information about the movement of an object. Multiple peculiar characteristics can be used to confirm the movement. For example, a rod movement from south to north on west side of dome (figure 4.20) can be confirmed through four characteristic patterns.

Figure 4.20: Schematic representation of movement of rod from south to north on the west side of dome.

Table 4.1: Four characteristic patterns for rod moving from south to north on west side of dome.

Highest first peak at 'West' sensor	<p>(Figures: 4.15 and 4.16(a))</p>
Time difference between first peaks at 'North' and 'South'	<p>(Figure 4.15)</p>
Higher output at 'South' at a later instance due to dragged water	<p>(Figures 4.15 and 4.16(b))</p>
Dips in the outputs at 'East' and 'North'	<p>(Figure 4.18)</p>

For better decision making it is always useful to have multiple cues about a stimulus. Combining information from multiple sensors is called multisensory integration and it is critical for intelligent systems [12]. In biological systems too, multisensory integration is an important aspect of decision making [13]. For example, in somatosensory system (which is related to information obtained from receptors in skin), spatial [14] and temporal [15] integration of information obtained from multiple points, takes place. ‘Multisensory’ could also imply multiple sensors - each sensing different type of modality, i.e. flow, temperature, humidity etc. In case of SA dome, it is about integration of information from multiple sensors sensing same modality. One of the advantages of multisensory integration for such a system is reduction of overall uncertainty. It also helps in improving reliability in cases where a sensor in the array stops functioning or malfunctions [12]. Therefore having 4 different types of information about movement of rod will make it easier to confirm the movement of object. Apart from these cues, the magnitudes of the peaks would provide information about the distance and speed of the movement.

A comprehensive database that contains information about aforementioned specifications for different combinations of speed and distances needs to be developed. More experiments can be conducted to obtain quantitative analysis of output of the sensors with regards to more complex movements and series of movements. The database can then be used to train machine learning models which in turn can be employed for automating data analysis and identifying the patterns in the outputs generated by unknown stimuli. With these improvements, an ISO-inspired sensing system would be able to discern movements in its vicinity and take decisions about its own positioning and maneuvering, accordingly.

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5

DESIGN AND FABRICATION OF DOME WITH HEMISPHERICAL ARRAY

This chapter discusses a novel approach of constructing hemispherical array which employs a technique of contractively wrapping a hemispherical surface with flexible polymer petals. This approach leverages the offerings from rapid prototyping technology and established standard MEMS fabrication processes. Hemispherical arrays of piezoresistive flow sensors (slowly adapting (SA) domes) are constructed with two types of petal wrappings, 4-petals and 8-petals, on a dome. Experimental results demonstrate that such a dome can provide three-dimensional information induced by the flow over the entire surface.

5.1 Introduction

Chapter 3 described, fabrication of SA and RA domes and their flow sensing abilities. The object detection abilities of these domes are explored in chapter 4. SA and RA domes used in these experiments are equipped with five sensors each. The domes are fabricated by manually placing individual pressure sensors on a 3D printed dome. It is important to find a way to fabricate a dome with more number of sensors and to avoid manual placement of individual sensors. This chapter discusses issues with construction of spherical arrays and then suggests a method to realize a spherical array with desired number of sensors mounted at predetermined locations on a sphere.

A dome shaped structure with array of flow sensors mounted on it, has promising applications in flow and object detection owing to spherical symmetry. Due to the rotational symmetry of the spherical surface, such an array facilitates spatial filtering or beam-forming. In addition, for a spherical array, the processing of data can be formulated in spherical harmonics domain, which facilitates efficient algorithms [1]. Benefits of spherical arrays have been explored in various applications in the past. Spherical arrays of acoustic sensors is a good example which exploit the aforementioned advantages [2]. ISO-inspired domes with an array of piezoresistive and piezoelectric sensors were used for flow sensing and direction detection [3]. Spherical array of optical micro-lenses was employed to construct a bio-inspired artificial compound eye [4, 5]. Considering these applications, constructing hemispherical designs featuring array of sensors placed at precise positions on a dome surface would be of great interest.

Micro-electro-mechanical-systems (MEMS) fabrication technology is well evolved over a few decades and is suitable for fabrication of arrays on a flat surface. It facilitates fabrication of miniature devices and thereby increasing the number of sensors in an array. However when it

comes to fabrication on non-planer or spherical surfaces, MEMS fabrication faces several challenges. The traditional MEMS techniques primarily support microfabrication on flat surfaces like silicon wafer. Conventional masks are flat and inflexible and therefore are not conformable to the hemispherical surfaces. It is difficult to pattern a curved surface using conventional photolithography due to issues like depth of field [6]. The depth of focus of most lithographic systems limits the range of topography of the substrate that can be lithographically patterned to approximately $\pm\lambda/2$, where λ is the wavelength of light used for exposure [7]. These issues can be addressed by having a flexible mask and an arrangement for making the exposure of UV light normal to the surface at all the points on hemisphere. Researchers have tried elastomeric masks [7] and innovative techniques for exposure [8, 9] as a solution to this problem. But these methods may not provide uniformity in the feature size of the devices across the hemispherical surface or they need complex arrangements in the lithography process, which could be both expensive and cumbersome.

Another approach is to carry out MEMS fabrication on a flat but stretchable surface with a cavity beneath it and then inflate the surface using thermal expansion of the gas within the cavity [10] or alternatively, stretching the surface on a hemispherical support [5, 11, 12]. But in these approaches, an arrangement or mechanism for the deformation of the stretchable substrate is required. Also, in cases where stretched substrate itself needs to serve as a sensing membrane, the tensions in the deformed base also add to the complexities. Moreover, the interconnects on a stretched substrate need to be either made up of a stretchable material [13, 14] or need supplementary modified MEMS processes like depositing interconnects on a pre-stretched membrane [15, 16]. These issues can be circumvented by using contractive wrapping of spherical surface using flexible petals.

There have been attempts to use hemispherical arrays of piezoresistive and piezoelectric sensors for underwater sensing [3]. However, the number of sensors in the array was limited (only five sensors) and each individual sensor was manually placed on the dome. This work aims at realizing a reliable and repeatable method to construct a dome with array of large number of sensors placed at precise positions on the dome, circumventing the manual placement of individual sensors. In this work, piezoresistive sensors are fabricated on a flexible liquid crystal polymer (LCP) petals leveraging conventional MEMS technology. Subsequently the petals are transferred onto a 3D printed dome structure, to form a dome with 17 sensors on its surface.

5.2 Contractive wrapping and design of polymer petals

5.2.1. Wrapping a sphere with petals

Coverage of a spherical surface by a flat paper is an interesting problem and one of its significant applications is associated with packaging industry. In order to achieve efficient material usage and mass production, researchers have attempted to find shapes with small area and perimeter to wrap a spherical surface. It is not possible to wrap a flat sheet conformably on an entire spherical surface without crumpling it. But this can be achieved if the flat sheet is divided into several ‘petals’ [17] and these petals are mounted on the sphere. Figure 5.1 shows ‘k-petal’ pattern which can be wrapped on a sphere, k being the number of petals that will cover a sphere. As the value of k increases, each petal in that scheme when placed on sphere, would show better conformity and the gaps between the petals would also be reduced. Figure 5.1(a) and 5.1(b) depict 3-petal and 4-petal designs to cover a sphere, respectively. Petals designed to cover a hemisphere would be half of the petals shown in Figure 5.1.

Figure 5.1: k -petal wrappings for a sphere; k is the number of petals: (a) 3-petal wrapping and (b) 4-petal wrapping [17].

Zhuang and Ju, in 2014 attempted to employ the strategy of wrapping a hemisphere using petals for building a tunable hemispherical platform for mounting non-stretching flexible device layers [18]. They constructed a pneumatically controllable hemisphere, employing an elastomeric membrane on which flexible polyimide petals can glide freely and thereby obtaining conformably mapped flexible polyimide layers on a curved surface. The tunability of the hemisphere could be critical in case of opto-electronic devices and therefore it could be worth to bear the complexities owing to the sliding parts of the tunable platform. However, in case of hemispherical array of diaphragm based sensors, a stable and rigid base which is devoid of the pneumatic actuation is required. A hemispherical array of piezoresistive sensors can be obtained if the sensing membrane patterned with sensing elements, itself is mounted on a stiff dome.

Tiling a dome with geodesic grid is an alternate way to cover a spherical surface, which was employed in fabrication of dome with electronic pixel arrays [19]. But the geodesic tiling can lead to complicated interconnections since the connecting lines for all the devices need to extend up to the base of the dome crossing the boundaries between the tiles on the way. Using petal

structures for coverage of dome would overcome this issue as petals continuously cover space from apex to the base of the dome. In this chapter the application of this strategy is demonstrated through contractive wrapping of dome using 4-petal and 8-petal designs.

5.2.2 Design of the petals

For a dome with radius r which is to be wrapped by k petals, the dimensions of each petal would be function of r and k . Figure 5.2(a) and 5.2(d) depict two cases in which a dome is covered by 4 and 8 petals respectively with a single petal highlighted in blue. Figure 5.2(b) and 5.2(e) show the dimensions of outline of the petals and the apex angles in respective cases. Figure 5.2(c) and 5.2(f) depict half petals with two parameters labeled. Parameter c is the distance of a point on centerline of the petal from the apex of the petal and parameter b represents the distance to be covered from the corresponding point, perpendicular to centerline, to reach the outline of the petal. The relationship between these two parameters is discussed in [17]; a half petal for a hemispherical dome with unit radius is given by $\{(c, b(c)) | 0 \leq c \leq \frac{\pi}{2}\}$ where,

$$b(c) = \arctan\left(\sin c \tan\left(\frac{\pi}{k}\right)\right) \quad \dots\dots (5.1)$$

Figure 5.2: Petal wrappings for hemispherical dome. 4-petal case: (a) 4-petal wrappings for a dome with one of the petals highlighted in blue, (b) dimensions of a petal in 4-petal case, and (c) a half petal in 4-petal case showing the parameters b and c . 8-petal case: (d) 8-petal wrappings for a dome with one of the petals highlighted in blue, (e) dimensions of a petal in 8-petal case, and (f) a half petal in 8-petal case showing the parameters b and c .

Once the petal outline is known, desired number of devices can be drawn on the petal during the mask design. In 4-petal case, each petal is patterned with 3 piezoresistive strain gauges, two on 30° latitude and one on 60° latitude; whereas in 8-petal case, each petal is patterned with two piezoresistive strain gauges, one on 30° latitude and one on 60° latitude.

5.3 Fabrication and assembly of hemispherical arrays

5.3.1 Design of the devices and masks

The design of piezoresistive strain gauge is the same for both 4-petal and 8-petal case. Each gold strain gauge is designed for a diaphragm of diameter 2 mm. The approach in deciding the dimension of the diaphragm is similar to the one mentioned in [20]. To determine the position of the gold piezoresistor on the diaphragm, simulation is carried out in COMSOL Multiphysics software. The main objective of the simulation is to investigate the distribution of stress on the surface of the diaphragm. Figure 5.3(a) depicts the geometry and dimensions of the diaphragm used in the simulation. The material of the diaphragm is set to be liquid crystal polymer (LCP). The thickness and diameter of the diaphragm are 25 μm and 2 mm, respectively. The edge of the diaphragm is fixed and a boundary load of 10 N/m^2 is applied on the top surface. Figure 5.3(b) shows a 3D plot of total displacement of the diaphragm with maximum displacement being 0.04 μm . Figure 5.3(c) depicts the variation in the xx component of the stress tensor along the length of a diameter along X axis of the diaphragm. The plot clearly shows that the polarity of the component changes at about 0.35 mm and 1.65 mm. The stress polarity is positive for the regions 0 - 0.35 mm and 1.65 – 2.00 mm. To maximize the sensor output, the gold piezoresistor need to be positioned in the region of same polarity of the stress and the regions of the opposite polarity should be avoided. Considering this aspect, the piezoresistor is positioned only in the region beyond radius 0.65 mm as shown in Figure 5.3(d).

Figure 5.3: Simulations for determining the positioning of piezoresistor: (a) Geometry of the diaphragm used in the COMSOL simulation. (b) A 3D profile showing the total displacement of the diaphragm under a boundary load of 10 N/m². (c) A line plot depicting xx component of the stress tensor along diameter of the diaphragm. (d) Pattern of the piezoresistor designed by taking the polarity of the stress into consideration.

Figure 5.4(a) shows a schematic of the lithography mask of 8-petal case, designed for fabrication of devices on 4-inch wafer. The mask is designed to have twelve petals (a dome would be covered by eight of such petals) and four piezoresistors for mounting at the apex of dome (a dome would need only one of these four). Figure 5.4(b) shows a schematic of one petal which possesses two gold piezoresistors with their contact pads at the base of the petal. The piezoresistors are positioned on the centerline of the petal in such a way that when the petal is mounted on the dome, the piezoresistors would lie on 60° and 30° latitudes. In other words, the

centers of the piezoresistors lie at distances of $\frac{\pi r}{6}$ and $\frac{\pi r}{3}$ from the apex of the petal. The zig-zag pattern of the piezoresistor and its dimensions are depicted in Figure 5.4(c) and 5.4(d) respectively. The zig-zag pattern with long radial sections and short tangential sections ensures that the change in resistance per unit strain is maximized [21]. The contact pads are placed at the lower end of the petal such that they will lie at the base of the dome and subsequently can be connected to connecting wires.

Figure 5.4: Schematics of mask: (a) The design of a 4-inch wafer mask for fabricating petals. (b) A single petal with two piezoresistor patterns on it. (c) A close up of the schematic of zig zag pattern of the piezoresistors. (d) The dimensions of the zig-zag pattern of a gold piezoresistor.

5.3.2 LCP as a substrate

LCP is a biocompatible, low cost material and its choice is made considering some unique properties of the material [22]. LCP thin film is flexible and can be used for laminating any shape which makes it suitable for forming polymer petals for dome coverage. It has a low moisture absorption coefficient of about 0.02%, and it doesn't react with acids, bases and various solvents, making it apt for fabrication of stable and durable sensors. Its melting point (290° C) is high enough to withstand photoresist baking during photolithography. The chemical stability and higher melting point make LCP compatible with MEMS lithography process, which in turn facilitates patterning of devices on LCP. Considering these aspects, LCP is an ideal candidate for fabrication of a flexible array of sensors. In past LCP has been used as a substrate in fabrication of MEMS based pressure sensors [23] and chemical sensors [24]. This is the first time that LCP is being employed in fabrication of a spherical array, owing to its aforementioned properties.

5.3.3 Fabrication of polymer petals

The device fabrication is carried out using 25 μm thick LCP (ULTRALAM 3850 from Rogers Corporation) as the substrate. Figure 5.5 shows the process steps carried out during the fabrication. The LCP is cut in a 4-inch wafer size and the copper cladding on both sides of the LCP is removed using copper etchant (Sigma Aldrich, product no. 667528). The bare LCP 4-inch sheet is then attached to a dummy silicon wafer using a 10 μm thick layer of photoresist AZ 9260 as an adhesion layer (Figure 5.5(a)). To improve the adhesion, the assembly is baked at 75 °C for 40 minutes. Following this, a 5 μm thick photoresist is spin-coated on the LCP (Figure 5.5(b)) and is patterned (Figure 5.5(c)) for the lift-off process. Layers of Cr (20 nm)/Au (100 nm) are deposited (Figure 5.5(d)) and the lift-off process is carried out to realize the gold piezoresistors on LCP. The intermediate layer of 20 nm thick Cr, helps in improving the

adhesion of Au on the LCP. During the last step of lift-off, when the wafer is immersed in acetone, the LCP is separated from the silicon wafer. In the end, a 25 μm thick LCP, with gold piezoresistors patterned on one side is obtained (Figure 5.5(e)).

Figure 5.5: Fabrication process: (a) Bare LCP after removing the copper cladding from both sides; (b) Spin-coating photoresist on LCP; (c) Patterning the photoresist by photolithography; (d) Sputtering Cr/Au layer on the patterned photoresist; (e) Removal of unwanted Cr/Au layer and the photoresist in Lift-off process.

Figure 5.6(a) depicts a photograph of a 4-inch wafer size LCP with twelve patterned petals and four single piezoresistors on it. The average value of the resistance of a gold piezoresistor is measured to be 957 Ω . A dome is to be covered by eight petals and a single piezoresistor at the apex. Figures 5.6(b) and 5.6(c) show close-ups of a petal and a single zig-zag patterned gold piezoresistor respectively. After the fabrication of LCP membranes, a thin protective layer of Sil-poxy (Smooth-On Inc.) is coated on them. The layer insulates the strain gauges and also protects them from mechanical damage. Sil-poxy is a soft and stretchable (elongation at break being

750%) material as compared to LCP. However the protective layer may reduce the sensitivity of the sensors.

Figure 5.6: Photographs of patterned polymer petals: (a) A 4-inch wafer size LCP, patterned with gold piezoresistors with twelve polymer petals and four single piezoresistors. (b) A single polymer petal with 2 gold piezoresistors on it with the contact pads of both the resistors provided at the base of the petal. (c) A zig-zag pattern of gold piezoresistor under microscope.

5.3.4 Assembly of polymer petals

Two types of parts are 3D printed – support pillars with a cavity at the top and a dome with sockets for the pillars to fit in. 3D printing is carried out with Fortus 360mc 3D printer (Stratasys Inc.) using Acrylonitrile butadiene styrene (ABS). Figure 5.7 illustrates how the two 3D printed parts and the petals are assembled. Figure 5.7(a) shows a schematic of a petal with two gold piezoresistors on it. Figure 5.7(b) shows a schematic of a support pillar with cavity - the diameter of the cavity is 2 mm, the thickness of the wall of the cavity is 0.4 mm and the depth of the cavity is 0.5 mm. To each petal, two support pillars are attached from hind side using non-conductive epoxy – EPO TEK H70E (Epoxy Technology Inc.), such that the cavity of pillars lie exactly beneath the piezoresistors, as shown in Figure 5.7(c). The two support pillars of each

petal are inserted into the sockets on the dome, assisting the mounting of petals on the dome as depicted in Figure 5.7(d). There are 17 sockets on the dome – 1 at the apex, 8 on 60° latitude and 8 on 30° latitude. The sockets on the dome are designed such that the support pillars precisely fit into them. At the apex of the dome, a single piezoresistor is mounted using a single support pillar. The support pillar structure has two functions – i) to ensure precise positioning of each piezoresistor on the dome and ii) to provide support and cavity for the piezoresistive diaphragm. Since the support pillar is already attached to the petal, the piezoresistive sensing membranes with its cavity are secured and are sustained through the process of placement of petals on the dome.

Figure 5.7: Schematics of different components of petal-dome assembly: (a) A petal with two patterned gold piezoresistors (b) A 3D printed support pillar with a cavity at the top (c) Back side of a petal after attaching two support pillars to the petal in such a way that the cavities on the pillars lie exactly beneath the gold piezoresistors (d) Mounting of a petal on the 3D printed dome. The support pillars fit into the cavities on the dome and the petal conformably attaches to the dome.

Figure 5.8(a) shows a dome with 4 petals and Figure 5.8(b) depicts a dome with 8 petals. In both the figures, apart from petals, a single device mounted at the apex can be seen. The dome is

placed on a support base with connecting wires passing through the holes provided on the base. The contact pads at the base of each petal are connected to respective wires using conductive epoxy EPO TEK H20E (Epoxy Technology Inc.). Figure 5.8(c) shows an 8-petal dome placed on a support base with all the contact pads connected to wires.

Figure 5.8: Photograph of domes after petals are mounted on them: (a) a dome with 4 petals (b) a dome with 8 petals (c) 8-petal dome with contact pads on the petals connected to wires using conductive epoxy.

From the wrinkles on the LCP membrane in Figure 5.8(a), it is evident that the conformal coverage in 4-petal case is not as good as that in 8-petal case. Since the cavity under each piezoresistor is secured through epoxy prior to the placement of the petal on dome, the sensors would still be functional. The petals on the 8-petal dome show better conformability and therefore 8-petal design is likely to be a preferred choice over 4-petal design.

The fabrication approach with polymer petals provides great flexibility in terms of size of dome, number of petals, number of devices per petal and dimensions of each device. In this work, domes with 4-petal and 8-petal designs are fabricated and the numbers of devices per petal are 3 and 2 for 4-petal and 8-petal cases, respectively. It is easy to extend the same approach to cover a dome with 6 or 10 petals and also to have more number of devices per petal. Considering the fact

that the contact pads for all the devices are lined up at the base of the petal, size of the contact pads is likely to be the limiting factor in increasing the number of devices per petal. The size of the piezoresistive strain gauge and the diameter of the cavity of the 3D printed support pillar can be varied to form sensors with different sensitivities as the need may be. However, the resolution of the 3D printer could be the limiting factor in scaling down individual sensor. As discussed earlier, LCP is a great choice for a flexible substrate but there are other flexible materials which can also be used as sensing membrane. For example, petals of polyvinylidene fluoride (PVDF) film patterned with electrodes can be used in constructing a dome with an array of piezoelectric sensors. To summarize, flexible patterned petals can be employed to form hemispherical arrays with different types and number of sensors.

5.4 Characterization of sensors

This section describes the experiments carried out for characterization of individual sensors in the hemispherical array. Each of the sensors is connected to a dedicated external Wheatstone's bridge circuit, each comprised of $560\ \Omega$ resistors and biased with a 5 V constant voltage source. Wheatstones's bridge circuits facilitate the recording of the change in resistances of the piezoresistive sensors in terms of change in voltage. The data is recorded in LABVIEW software using National Instruments data acquisition card (NI-DAQ) system USB-6289 M-series model.

In order to determine response time, the sensor is initially subjected to no air flow, which is followed by the introduction of an instantaneous air flow of 1 m/s (measured by BESTONE BE816 Anemometer). Figure 5.9(a) depicts the output of the sensor showing a step increase in the output. The response time is the time required for sensor output to reach 90% of the maximum value from 10% of the maximum value. The two levels are marked in the plot in

Figure 8(a) and the difference between the corresponding time values is 0.58 s. When the stimulus is removed instantaneously, it takes 2.35 s for the sensor to decrease to 36.8% of the maximum value, as depicted in Figure 5.9(b). For a set of three sensors, the average values of response time for positive and negative step are observed to be 0.60 s and 2.14 s respectively, with standard deviation being 0.07 s and 0.27 s, respectively. The response time of 0.6 s is slow as compared to commercial pressure sensors with silicon membranes which have response times of the order of a few milliseconds. However, it is sufficient for flow sensing applications where stimulus doesn't change rapidly. The slow response of the sensor can be attributed to the mechanical properties of LCP. Young's modulus of LCP is 2.2 GPa, which is about two orders lower than that of silicon (185 GPa). However, response time can be improved further either by reducing the diameter of the diaphragm or increasing the thickness of the diaphragm of the sensor.

Figure 5.9. Time response of the sensor (a) positive step (b) negative step

To determine the range of a sensor, response of the sensor facing the flow is recorded for speeds of 0.2, 0.5, 1, 3, 5, 10 and 15 m/s, in a wind tunnel. It is observed that for 15 m/s speed, the sensor output reaches to a value of 20.5 mV and tends to become saturated as shown in Figure

5.10. The response of the sensor is linear for speeds 0.2 m/s to 5 m/s. For the linear region, dynamic range of the sensor is 25:1. However with appropriate calibration, the sensor could be employed for speeds up to 15 m/s.

Figure 5.10. Output of the sensor while facing the flow of speeds ranging from 0.2 to 15 m/s.

Figure 5.11(a) depicts a linear fit for the output of the sensor for speeds up to 5 m/s. Sensitivity of the sensor is determined by the slope of the linear fit. The R-squared value for the fit is 97% and the sensitivity is 2.86 mV/(m/s). The sensitivity is comparable to sensitivities achieved by gold-piezoresistor-based flow sensors fabricated in the past [25].

To determine the accuracy of the sensors, the outputs of eight different sensors are recorded for a flow of speed 5 m/s. From the output of each sensor, flow speed is calculated using the linear fit equation obtained from the plot in Figure 5.11(a). Figure 5.11(b) depicts the distribution of calculated flow speeds around the true value of the flow speed. The relative error is observed to be around 4.5%.

Figure 5.11. (a) Linear fit for the output of the sensor for speeds 0.2, 0.5, 1.0, 3.0 and 5.0 m/s. (b) Distribution of calculated flow speeds around the true value of flow speed of 5 m/s.

For a sensor, noise is a critical factor that may adversely affect its performance. In order to investigate noise, the peak-to-peak noise level is determined for 4 different sensors for each of the speeds 0.2, 0.5, 1, 3 and 5 m/s. It is observed that the noise level is at around an average value of 0.37 mV (with a standard deviation of 0.07 mV), which is at least an order of magnitude lower than the output of the sensor even at the lowest speed of 0.2 m/s.

5.5 Flow experiments

This section elucidates the proof of concept experiments demonstrating the flow sensing and direction detection abilities of the dome with 8 petals. For conducting experiments and carrying out the analysis the petals and the sensors are labeled as shown in Figure 5.12. Petals are labeled from A to H, the sensors on the petals are numbered from 1 to 16 and the sensor at the apex is numbered 17.

Figure 5.12: Nomenclature of the petals and sensors on the dome: The petals are labeled from A to H and the sensors are numbered from 1 to 16 with the sensor at the apex numbered 17. Letter 'L' denotes that the position of the sensor on a petal is lower i.e. towards the base of the dome whereas letter 'U' indicates that the sensor is at an upper level i.e. towards the apex of the dome.

The dome is tested for its flow sensing and direction detection capabilities in an open circuit subsonic wind tunnel equipped with a flow meter. The test section of the wind tunnel is of dimension $0.4 \text{ m} \times 0.4 \text{ m} \times 1.4 \text{ m}$. The dome is mounted on a rotatable base so that the orientation of the dome can be changed during the experiment as shown in Figure 5.13.

Figure 5.13: Experimental setup: (a) A block diagram depicting various components of the experimental setup and the Wheatstone's bridge (b) The dome is mounted on a rotatable base and is placed inside a wind tunnel.

5.5.1 Flow velocity sensing

The first experiment is aimed at investigating the effect of varying flow velocities on the output of the sensors on the dome. The dome is placed in such a way that petal F (i.e. sensors 11 and 12) faces the flow and petal B (sensors 3 and 4) lies on the other side. For different speeds of the wind flow outputs of sensors 3, 4, 11 and 12 are recorded. The second set of experiments is targeted towards exploring the direction detection ability of the dome. The flow speed is set at 5 m/s and the dome is rotated to make different petals face the flow. Initially petal B is made to face the flow and the base is rotated in counter-clockwise fashion, 45° at a time, to bring the next petal facing the flow and data is recorded for each of the case.

Owing to the variations in fabrication, circuits and packaging processes, there could be discrepancies in the outputs of all the sensors for the same stimulus. A calibration process is carried out to bring parity amongst the sensors. The output values mentioned in the discussions are values obtained after the calibration.

Figure 5.14 depicts how the outputs of sensors 12 and sensor 4, change with respect to time when the dome is hit by an oncoming wind flow. After the on-set of the flow, the output of the sensor facing the flow rises to a higher value of about 18 mV than that of the sensor on the other side of the dome which is about 12 mV. Not only the output for sensor 12 is higher, its rate of increase (~ 1.7 mV/s) is also higher than that of sensor 4 (~ 0.9 mV/s). As the flow is directly imparting force on the diaphragm of sensor 12 almost head-on (unlike for sensor 4), the bending of diaphragm is faster, resulting in greater slope during the rise of the sensor output.

Figure 5.14: Output of the sensors 4 and 12 when petal F on the dome faces the air flow of speed 5 m/s.

Figure 5.15 shows the outputs of sensors 3, 4, 11 and 12 for flow speeds between 0.2 m/s and 5 m/s. From the plot, it can be observed that the outputs of the sensors on petal F, which is facing the flow, show more increase in comparison with the outputs of the sensors on petal B, which is on the opposite side of the flow. The output of sensor 12, which is facing the flow and closer towards the apex of the dome, is the maximum amongst all the sensors. The difference in the outputs is due to the disparate positions of the sensors on the dome and it basically demonstrates the inherent advantage of spatial filtering that a dome structure provides. The observations from figures 5.14 and 5.15 indicate that through the pattern of outputs of the sensors on a dome, the direction of the stimulus or flow can be determined. Also the speed of the flow can be obtained from the output of the sensor that shows maximum output – sensor 12 in this case.

Figure 5.15: Output of the sensors at 3, 4, 11 and 12 when petal F on the dome faces the air flow of speeds 0.2 m/s, 0.5 m/s, 1 m/s, 3 m/s and 5 m/s.

Considering the fact that sensor 11 is tilted at 60 degrees with respect to the direction of flow (as compared to 30 degrees of sensor 12), it could be expected to show more output than sensor 12 (Figure 5.16(a)). However, though it faces the flow, it shows lower output as compared to sensor

12. There could be multiple possibilities behind this discrepancy. Due to the presence of the support disc beneath the dome, sensor 11 may not be facing an uninterrupted flow. The edge of the support disc could be reducing the flow faced by sensor 11, due to boundary layer or a wake region formed after its edge. Horseshoe vortices could be also a probable reason behind the discrepancy. For moderate and high Reynolds numbers, upstream of an obstacle, horseshoe vortices are formed [26]. An example of this is shown in Figure 5.16(b) [27], which corresponds to Reynolds number 1400, in which horseshoe vortex can be seen upstream of the hemisphere. Higher the Reynolds number, more is the circulation of the horseshoe vorticity [26]. Tamai et al [28] studied vortices around hemispherical humps in detail and found that the stagnation point on the hemisphere is at a height of about half of the radius. The Reynolds numbers for the flow speeds used in wind tunnel experiment range from 500 for 0.2 m/s to 12000 for 5 m/s. Considering the Reynolds numbers involved, the horseshoed vortices are likely to be formed. The vorticity may affect the flow reaching sensor 11 and therefore it could be a probable reason behind the discrepancy.

Figure 5.16: (a) Schematic of dome with support base showing positions of sensor 11 and sensor 12 (b) Side view of horseshoe vortex formation, upstream of the hemisphere ($Re = 1.4 \times 10^3$) [27].

5.5.2 Flow direction detection

The second experiment is aimed at investigating how the outputs of the sensors on the dome vary with respect to change in the orientation of dome for same flow speed. Figure 5.17 depicts the variation in the outputs of the sensors on the dome when the dome is rotated counter-clockwise by 45° . When petal B is facing the flow, sensors 3 and 4 show the maximum output, whereas sensors 11 and 12 show the least. As the dome is rotated to bring petal D to face the flow, the outputs at sensors 3, 4, 11 and 12 are almost at equal level because now they are in equivalent position on the dome with respect to the flow. As the dome is rotated further, to bring petal F face the flow, output of sensor 11 and 12 rises and that of sensors 3 and 4 drops. From the pattern it is clear that the dome can clearly determine the direction of the incoming flow.

Figure 5.17: Output of the sensors 3, 4 (petal B) and 11, 12 (petal F) when dome is rotated in steps of 45° to bring each petal facing the air flow of speed 5 m/s. The error bars represent the standard deviation in the respective outputs over 3 runs.

Ideally, the outputs of the sensors for position A should be equal to respective outputs for position C. However it is not the case and this could be due to error in the rotation of the base caused by lack of precise mechanized control. Also, the error bars in figure 5.17 suggest that for one particular sensor (eg. sensor 4), there may not be a significant difference in output for position B as compared to that for positions A or C. This is confirmed through a paired t-test between the outputs of sensor 4 at positions B and C ($p > 0.01$) for a data set of 5 runs. A paired t-test is conducted to compare the output of sensor 4 at position B to its outputs at position D. It is observed that there is a significant difference between the output at positions B (Mean = 19.2 mV, SD = 0.5 mV) and D (Mean = 11.8 mV, SD = 0.8 mV), conditions; $t(4) = 11.9$, $p < 0.01$. This implies that one sensor alone may not be able to provide sufficient evidence to distinguish two positions separated by 45° . However, pattern of all the sensors on the dome, does provide sufficient information to obtain a resolution of 45° .

5.5.3 Output profile over surface

An array of sensors mounted on a hemisphere can provide the output profile over the entire surface. Figure 5.18 depicts the output surface profiles constructed using the outputs of the sensors on the dome for three different speeds, namely 0.2, 1 and 5 m/s. The colour scale for each of the profile is same so that the increase in the speed of flow is reflected in the profile. The increase in the relative outputs of the sensors with respect to speed can be compared through the ratio of outputs. For example, ratio of outputs of sensors towards apex, on front and back end (denoted by black arrows in figure 5.18) goes on reducing as the speed increases. The ratio is 4.8 for speed 0.2 m/s, 2.0 for speed 1.0 m/s and 1.6 for speed 5.0 m/s. As discussed in chapter 3, fluid dynamics experiments with flow over hemisphere demonstrate that the disparity between

the pressure coefficients at the positions of these two sensors would increase with increasing speed. But this doesn't reflect in the outputs. This is expected considering the response of individual sensors shown in figure 5.10. For higher speeds the sensor output goes towards saturation, bringing down the ratio of the outputs. It also implies that the directionality of the hemispherical array is better at lower speeds. Directionality of the array can be tuned by modifying the parameters of individual sensors to adjust their range. For example, a hemispherical array of sensors with thicker diaphragms will show improved directionality at higher speeds.

Figure 5.18: Output profiles across the dome surface when placed in the airflow of speeds 0.2 m/s, 1 m/s and 5 m/s.

In Figure 5.18, it can be seen that the sensors facing the flow show higher outputs. The sensor on 60° latitude and in line with the flow shows the maximum output amongst all the sensors. The output at the sensors towards apex of a petal is more than that at the base of the petal. This

observation is consistent with the observation in the previous sub-sections. Moreover, this holds true for a petal in any position with respect to the incoming flow. As mentioned earlier, one of the probable reasons behind this may be horseshoe vortices formed upstream of the dome. The vorticity advects downstream by stretching on either side of the dome, thereby producing vorticity wrapped around the dome which then extends into downstream [26]. Wood et al [29] have shown it in their work through time averaged streamlines on the bottom wall and on the surface of the dome (Figure 5.19). The horseshoe vortices moving downstream from either side of the dome can be seen in figure 5.19.

Figure 5.19: Time-averaged streamlines on the base and on dome surface, showing horseshoe vortex moving down the streamline along either sides of the hemisphere (top view) [29].

This vorticity around the dome could be affecting all the sensors towards the base of the dome. It would be interesting to conduct fluid dynamical experiments to visualize the flows around the dome. Flow visualization would also help in directly comparing the pattern of outputs of 17 sensors with respect to actual flow.

There have been successful attempts of fabricating dome shaped sensors [3, 30], but owing to the device geometries and less dense arrays, output profiles over entire surface of the dome representing the effect of the flow over it, have not been constructed so far. The surface profiles from Figure 5.18 suggest that fabrication strategy with polymer petals can be employed in

applications such as artificial smart skin where profiling of a stimulus over the entire surface is required.

5.5.4 Alternate ways for sensing flow and direction

A hemispherical dome covered with an array of sensors, provides opportunity for alternate methods to sense the flow and direction. One such alternative is inspired from the fact that the biological mechanoreceptors have a threshold level for detection of stimulus. If the stimulus is below the threshold level, its presence is not reported to brain. However if it is above the level then it is recognized and its information is transmitted to brain. Simplistically, this can be considered as a binary system where each sensor distinguishes two states – stimulus below a threshold level and stimulus above the threshold level. If each sensor on the dome is capable of distinguishing the aforementioned two states, then the dome is a hemispherical array which possesses digital sensing ability. Stimulus below the threshold is represented by 0 and stimulus above the threshold is represented by 1. When a flow hits the dome, depending on the speed of the flow and the position of a sensor on the dome, it will either be on (1) or off (0). So, flow with a particular direction and speed would have a pattern of on and off sensors from the hemispherical array. This kind of array can be called spatially digitized hemispherical array of sensors.

In 2014, Choi et al proposed spatially digitized tactile pressure sensor in which a particular number of pressure levels could be recognized by the sensor [31]. These sensors do not provide signal for a continuous range of pressure, but they are triggered only at certain values. The main advantage of these sensors is that they have low noise and can be designed to be responsive to different pressure levels. The piezoresistive pressure sensors on the polymer petals can sense continuous pressure values within a certain range and they are structurally and functionally

different from the digitized pressure sensors. However, their response or outputs can be processed to get spatially digitized profile over the dome surface. Figure 5.20 depicts such output profiles for four different speeds – 0.2, 0.5, 1 and 3 m/s. In this case the sensor output threshold is defined as 5.8 mV which corresponds to a specific pressure value. At flow speed of 0.2 m/s, none of the sensors on the dome has output more than the threshold value. At flow speed of 0.5 m/s, only one sensor that faces the flow head-on, has its output exceeding the threshold value. The number of sensors representing ‘on’ state increases further at speed of 1 m/s and eventually at speed 3 m/s all of the sensors on the dome are showing ‘on’ state.

Figure 5.20: Spatially digitized output profiles across the dome surface when placed in the airflow of speeds of 0.2, 0.5, 1 and 3 m/s.

The dome sensor reaches to saturation level at 3 m/s, i.e. it cannot sense speeds above 3 m/s with threshold of 5.8 mV. In other words, with this particular threshold value, the dome can provide spatially digitized information about flows for speeds up to 3 m/s. Threshold value can be

decided based on the sensing requirement or the relevant range of stimulus. Lower threshold value would imply that the flows at lower speeds are of interest and higher threshold value would enable the sensing in higher speed range. The saturation level of the dome will change based on the threshold value. The speeds at which saturation occurs can be considered as an upper limit of safe speeds for the underwater vehicle. So, a spatially digitized dome sensor detects speeds and directions of flows within a certain range and is oblivious to the speeds outside the range. Considering that individual sensor has only two states, the data provided by the dome would have low noise. It is capable of conveying only the crucial information such as flow that triggers the threshold level, flow that causes saturation and a few levels between these two limits.

5.6 Conclusions

In this work, MEMS fabrication technology and rapid prototyping technology are combined with a novel strategy to cover a hemispherical surface with polymer petals to form a dome equipped with a densely packed array of 17 piezoresistive sensors. Experiments demonstrated the capability of such a dome to provide information about flow speed, the direction of the approach of flow and the output profile over the entire surface of the dome.

The petal design, number of sensors on each petal and sensor parameters can be chosen based on different requirements. The fabrication methods and materials presented in this chapter will assist in formation of compact arrays with 3D configuration. The proposed strategy could be useful in biomimetic structures such as artificial skin, compound eyes as well as acoustic spherical arrays which have complex morphologies in three dimensions. This warrants further explorations about MEMS-compatible flexible substrates, flexible sensing materials and designs that are suitable for different geometries and applications.

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6

CONCLUSIONS AND FUTURE WORK

This chapter summarizes the work conducted under this project and presents conclusions and major contributions. It then outlines the scope for future work and elaborates on the main directions in which this work can progress.

6.1 Conclusions

The goal of this project was to enhance the sensing capabilities of AUVs through bio-inspirations drawn from ISOs on crocodiles. A comprehensive literature review was conducted which provided a better perspective about sensing limitations of AUVs and characteristics of ISOs that can provide cues in development of an ISO-inspired mechanoreceptive system. It also helped in understanding various aspects of a bio-inspired sensing systems developed in past. Based on the knowledge obtained from literature review, achievable objectives were outlined and the work undertaken was divided into three strands.

The first strand involved fabrication of ISO-inspired dome shaped sensors and conducting proof of concept experiments. Dome shaped sensors were developed to incorporate three characteristics of ISOs – i) SA and RA receptors associated with ISOs, ii) dome shape and iii) mechanoreceptors on the surface of dome. SA dome was realized using piezoresistive sensors and RA dome was constructed using piezoelectric sensors. Through proof of concept experiments, the ability of the domes to sense flows and direction of stimulus was demonstrated. The feasibility of SA domes in real applications was also investigated through towing experiments and sea trials.

The work in second strand was related to investigating the object detection ability of SA domes. Owing to their hemispherical shape, domes can provide information about object movement through the patterns of both, the magnitudes of the peak outputs of different sensors and the outputs of individual sensors over a period of time. The study demonstrated that the SA domes are capable of detecting direction, speed and distance at which the movement occurs.

The third strand is focused on fabricating a dome structure with 17 sensors mounted on its surface. This was achieved by contractively wrapping liquid crystal polymer petals on a 3D

printed dome. The dome was successfully tested for flow sensing and direction detection and owing to the dense array of sensors, the dome is also useful for obtaining profile of flow over the dome surface. The three strands with their key aspects are presented in Figure 6.1.

Figure 6.1: Three strands in which the work undertaken in this project is categorized.

6.2 Original contributions

The work done across the three strands mentioned in the previous section, has resulted in some original contributions to the fields of bio-inspiration, underwater hydrodynamic sensing and hemispherical array fabrication. The major contributions of this project are listed below.

1. Proposal of a passive hydrodynamic mechanoreceptive system inspired from ISOs on crocodiles.

2. Fabrication of slowly adapting (SA) and rapidly adapting (RA) domes, employing piezoresistive and piezoelectric pressure sensors, respectively.
3. Design and conduction of experiments for confirming the flow sensing and direction detection ability of both SA and RA domes.
4. Design and conduction of experiments for demonstrating the feasibility of employing SA domes on underwater vehicles and in on-field scenarios through sea trial experiments.
5. Design and conduction of experiments for confirming the object detection ability of SA domes.
6. Proposal, design and fabrication of a dome with 17 sensors by employing contractive wrapping of polymer petals on 3D printed dome.
7. Demonstration of applicability of densely packed hemispherical arrays of sensors in flow sensing, direction detection and profiling flows over the entire surface of the dome.

6.3 Future work

The objectives achieved in this project comprise of three broad strands – proposal of the idea and proof concept experiments, object detection, and fabrication of dense hemispherical array. If we are to envision the development of an ISO-inspired comprehensive passive mechanoreceptive system, the work accomplished till now provides a platform and paves way for further progress. There is a wide scope for development in each of the aspect – fabrication of dome, flow sensing, object detection and algorithms for interpretation of data.

6.3.1 Fabrication of RA dome using contractive wrapping

An SA dome with 17 piezoresistors was constructed using contractive wrapping of polymer petals. In a similar way, an RA dome can be fabricated. This can be achieved by using flexible piezoelectric substrates like polyvinylidene fluoride (PVDF) films. An RA dome with a dense hemispherical array of sensors would provide output patterns that reflect the effect of oscillating pressures on the entire surface of the dome. The ability to capture information about oscillating pressures with greater resolution, would make the sensing system more comprehensive. Patterning electrodes and drawing contacts from both the sides of a piezoelectric film could be a concern during fabrication.

6.3.2 Mechanical high pass filtering mechanism

A hydrodynamic passive mechanoreceptive system needs to be capable of receiving different types of stimuli, e.g. steady pressures caused by flows or an oscillating pressure originated from movements of animals. In proof of concept experiments discussed in chapter 3, sensing capability of SA dome was tested with steady pressures and that of RA dome was investigated using oscillating pressures. In laboratory, stimuli of various types can be controlled and that makes it easy to test them independently. However, in reality, a mechanoreceptive system on an AUV moving in water would be subjected to variety of mechanical stimuli simultaneously. This may result in one type of signal interfering with another. It would be ideal for receptors in sensing system to mask a certain type of signal while sensing the other. Mechanosensing systems in nature have figured out how to achieve this masking.

RA receptors in crocodiles are associated lamellated corpuscles, which are similar to Pacinian corpuscles in mammals. Pacinian corpuscles are made up of concentric lamellae with

interconnections between neighboring lamellae [1]. The space between two lamellae is filled with viscous interlamellar fluid. Static forces applied on the structure are carried by the outer lamellae. This structure allows only dynamic signals to reach the core containing the nerve ending situated at the center. The dimensions of the structure are of the order of a few hundred micrometers as depicted in Figure 6.2.

Figure 6.2: Schematic of longitudinal and transverse cross sections of Pacinian corpuscles depicting its components and dimensions.

An artificial lamellar corpuscle could provide a mechanical filtering facility to an ISO-inspired mechanoreceptive system. However there are several hurdles in accomplishing this objective, from perspective of design, materials and fabrication mechanisms. It would be challenging to construct an artificial corpuscle with concentric layers of lamellae with viscous fluid filled between them at the micrometer scale. As a starting point, a simplified, scaled up model can be designed with just flat layers of lamellae (instead of concentric and enclosed). Materials like hydrogels could be useful to construct such a lamellar structure. Hydrogels are three dimensional crosslinked networks of hydrophilic polymers capable of retaining large volumes of water as

shown in figure 6.3. They are either chemically or physically crosslinked and possess unique structural and mechanical properties that can be tailored to specific requirements [2].

Figure 6.3: A schematic showing polymer chains and self-crosslinked flexible hydrogel structure with crosslinking points (red) and water molecules (blue) entrapped within its network.

Hydrogels, owing to their capacity to contain water, would be suitable as interlamellar fluid. Hydrogels with higher crosslinker concentration have fewer cavities to contain water molecules. It implies that hydrogels can be synthesized without or with very less amount of water, making them a probable candidate in forming lamellae as well. After an artificial lamellar corpuscle is successfully developed, its integration with RA dome would also be an interesting problem to solve. Overall, an artificial lamellar corpuscle would be a fascinating endeavor for engineers, materials scientists and physicists.

6.3.3 Improvements in contractive wrapping method

In chapter 5, it was demonstrated that contractive wrapping of patterned polymer petals can successfully provide dense hemispherical arrays of sensors. However, the fabrication process involves manual handling, which limits the downscaling of the dome or individual sensors. There are two steps where manual handling may have critical effects on downscaling – i) pillar

placement and ii) contact pad connections. It is disadvantageous to place the support pillars manually and it does affect accuracy and repeatability adversely, especially when the sensor dimensions need to be scaled down. As far as this work is concerned, the manual placement gives satisfactory results primarily due to the sensor size being on the millimeter-scale. As the sensor dimensions are scaled down much below the millimeter range, an alternative method has to be sought to replace the manual placement of support pillars. One possible solution is to form support structures around the strain gauges using materials like SU8 in MEMS fabrication. The strain gauge needs a support around its periphery so that it forms a diaphragm with a cavity beneath it. This can be achieved by well-like SU-8 structures possessing high aspect ratio [3]. Figure 6.4 illustrates one possible SU-8 structure supporting the diaphragm with a piezoresistor.

Figure 6.4: Well-like structure of SU-8, fabricated through MEMS fabrication processes, can replace 3D printed support pillars.

Contact pad connection is the main bottleneck for downscaling both, petals and devices. The contact pads of all the devices on a petal are lined up at the base of the petal. This becomes a limiting factor for petal downsizing and increasing the number of devices per petal. As of now this issue would be the most critical limiting factor that decides the possible dimensions. This

issue can be addressed if a method is devised to form connections by either MEMS fabrication technology or conductive printing technology.

6.3.4 Employing multiple SA and RA domes

The experiments conducted in this project were designed to test the sensing capabilities of individual SA or RA domes. However the vision for an ISO-inspired sensing system includes multiple SA and RA domes mounted on an AUV. With an array of SA and RA domes, an AUV can be aware of even small movements close to a specific section of the AUV. Surfaces of different sections of an AUV may have different curvatures and therefore will be subjected to different flow patterns. The outputs of SA and RA domes would also be functions of the curvature of the surface on which they are mounted. This factor adds to the complexity and it will have to be taken into account while calibrating each dome. Experiments with multiple domes will involve much greater number of sensors and will lead to a huge amount of data. Therefore, before embarking on these experiments, it is very important to be able to fabricate both SA and RA domes with high reliability. Also, manual analysis of such a huge amount of data is a daunting task and therefore needs to be automated using tools like ‘Python’ programming language.

6.3.5 Employing intelligent algorithms for data interpretation

Proof of concept experiments with SA and RA domes were carried out and their flow sensing, direction detection and object detection abilities were demonstrated. However, considering the fact that the SA and RA domes are part of a sensing system, it is also interesting to see if the system can predict the reasons or causes behind a stimulus using advanced data processing algorithms and techniques. For example, if an SA dome receives a pressure stimulus, based on

the combination of the outputs of all the sensors on it - the time lags, duration of the pulse and temporal patterns in the outputs, can the system tell - (a) what is the cause behind the signal – is it movement of an object or is it a flow? (b) In case it is an object, what is the direction of movement of the object? (c) At what distance from the dome, the movement occurred? (d) What is the size and shape of the object?

Queries like these can be answered by finding patterns in the data, through artificial intelligence or machine learning techniques [4]. For example, supervised machine learning technique predicts a model based on a large set of training data, which is provided in form of input-output. In this case, the training data would contain outputs of all the sensors on a dome for various combinations of input features like flow, object size, object shape, distance and direction of movement and so on. Based on the training data, a model is created to predict the outcome of any new data that is input. Figure 6.5 shows process steps involved in supervised machine learning. Based on the type of outputs of the data, supervised machine learning can be classified into two categories – classification and regression. If the outputs of the data are discrete or categorical variables, then it is called ‘classification’. For example, if output of each observation indicates that the stimulus is generated by one of the two sources - flow or object movement, then it is a classification problem. On the other hand, if the outputs of the data are continuous or real numbers, then it is called ‘regression’. For example, if the outputs of the data provide information about speed of a passing object, which is a continuous numerical variable, then it is a regression problem. So, from the list of queries mentioned earlier, the first query - (a) can be answered using classification and rest of the queries - (b), (c) and (d) can be answered using regression.

Figure 6.5: Supervised machine learning: Various building blocks and the flow of the process.

Considering the number of input variables involved (SA dome, RA dome, flows, object movements, speed, distance, direction, etc.) and output parameters (magnitudes of outputs of multiple sensors, variation in output with time, etc.), a machine learning problem is bound to be complex. It is likely that such a complex problem will have to be split into independent single output problems [5]. As shown in figure 6.5, there are several steps involved in a supervised machine learning technique. A large training data set warrants meticulous collection of data of pertinent observations. Moreover, choice of algorithm, efficiency in execution and speed of execution play a critical role in the success of the machine learning approach. A fast, efficient and accurate prediction based on the received mechanical signal is what an AUV needs for decision making and maneuvering. Exploring machine learning and other statistical techniques with respect to ISO-inspired SA and RA domes would be a vital step in achieving it.

6.3.6 Looking beyond mechanoreception

Though this project has primarily focused on mechanoreception in ISOs [6, 7], it is worth being reminded that ISOs also play an important role in the form of pH and temperature sensors [8]. The ability of sensing multiple types of stimuli is a unique feature of ISOs and there is no equivalent of this in sensing systems of vertebrates. It is but obvious that an ISO-inspired dome with multi-sensing abilities would be preferred over one with only mechanosensing capacity. The vision for an ISO-inspired mechanoreceptive system can be expanded to a multi-sensing system by mimicking the structures and mechanisms that lend ISOs the ability to sense multiple types of stimuli.

Though it is proven that ISOs have pH and temperature sensing capabilities, more in-depth knowledge about structural features and processes involved in the sensing, are yet to be revealed. Information about types of receptors and their innervation needs to be explored. Once there is sufficient clarity about structural, functional and neural aspects associated with pH and temperature sensing, these features can be included in ISO-inspired domes. To develop multi-sensory devices, materials which are sensitive to multiple types of stimuli could be useful. For example, hydrogels are sensitive to pH value and temperature [2] and their mechanical properties also allow to develop sensors for mechanical stimuli [9]. This implies that there is a lot of scope for researchers from various fields – biology, bio-inspiration/biomimetics and materials science. As far as bio-inspiration is concerned, this work would pave way to new research associated with bio-inspiration from multi-sensory abilities of ISOs to improve sensing systems for AUVs.

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List of Publications

(A) Journal Papers

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(C) Conference Papers

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