DEVELOPMENT AND TESTING OF BIO-INSPIRED
MICROELECTROMECHANICAL PRESSURE SENSOR
ARRAYS FOR INCREASED SITUATIONAL
AWARENESS FOR MARINE VEHICLES

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Abstract
The lateral line found on most species of fish is a sensory organ without analog in humans. Using sensory feedback from the lateral line, fish are able to track prey, school, avoid obstacles, and detect vortical flow structures. Composed of both a superficial component, and a component contained within canals beneath the fish’s skin, the lateral line acts in a similar fashion to an array of differential pressure sensors. In an effort to enhance the situational and environmental awareness of marine vehicles, lateral-line-inspired pressure sensor arrays were developed to mimic the enhanced sensory capabilities observed in fish.

Three flexible and waterproof pressure sensor arrays were fabricated for use as a surface-mounted ‘smart skin’ on marine vehicles. Two of the sensor arrays were based around the use of commercially available piezoresistive sensor dies, with innovative packaging schemes to allow for flexibility and underwater operation. The sensor arrays employed liquid crystal polymer and flexible printed circuit board substrates with metallic circuits and silicone encapsulation. The third sensor array employed a novel nanocomposite material set that allowed for the fabrication of a completely flexible sensor array. All three sensors were surface mounted on the curved hull of an autonomous kayak vehicle, and tested in both pool and reservoir environments. Results demonstrated that all three sensors were operational while deployed on the autonomous vehicle, and provided an accurate means for monitoring the vehicle dynamics.

(Some figures may appear in colour only in the online journal)

1. Introduction

In an effort to improve the situational awareness of maritime devices, microelectromechanical (MEMS) pressure sensors are being developed for use on a wide array of surface and underwater vehicles. This paper will outline the biological inspiration behind the development of MEMS pressure sensor arrays, as well as identifying applications in engineered
systems that are analogous to behaviors found in nature. The development and fabrication of surface-mounted MEMS pressure sensor arrays will be discussed, and the testing and calibration of the sensor arrays will be outlined. Finally, the implementation and deployment of multiple MEMS sensor arrays on the hull of an autonomous surface vehicle will be presented along with results from recent field experiments.

1.1. Biological inspiration

Efforts to increase the situational awareness of marine vehicles operating in confined and hazardous environments have drawn inspiration from the enhanced sensory capabilities provided by the lateral line organ found in fish and some amphibian species. Of particular interest was the ability of the Mexican Blind Cave Fish (Astyanax fasciatus mexicanus) to navigate subterranean caves, despite eyes that have degenerated due to living in a world devoid of light. In place of sight as a primary means for detecting and avoiding obstacles, the cave fish rely on their lateral line for navigation, feeding, and other essential behaviors [1-4].

The fish lateral line is composed of two primary components, superficial neuromasts and a trunk canal system. Superficial neuromasts are located on the surface of the skin, exposed to the mean flow along the fish body, and provide feedback about the DC component of the flow. Alternatively, the trunk canal system is composed of neuromasts contained within canals beneath the fish’s skin, and connected to the exterior flow through a series of pores. When it is subjected to a pressure gradient between pores, a localized flow is induced within the canal, stimulating the neuromasts within the canal. In this way, the lateral line canal system acts in a similar fashion to a series of differential pressure sensors mounted on the side of the fish [3, 5].

1.2. Pressure sensing on hulls

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

Experiments using a hydrofoil constructed with pressure taps on the foil surface indicated that the shape and location of a stationary obstruction can be detected using pressure sensor feedback alone [5, 6]. While existing sensor technology greatly limited the distance at which an obstruction could be detected, the experiments demonstrated the potential for increasing environmental awareness for marine vehicles using a passive detection technique. Such a passive technique could be of great benefit for operation in noisy, cluttered environments, or where visual navigation is impaired due to a lack of light or poor water clarity. Passive methods for improving vehicle awareness are also attractive for missions where stealth and quiet operation are desirable.

It is believed that the detection of strong vortex structures shed by a vehicle during maneuvering could be utilized to either increase vehicle maneuverability, or decrease the drag associated with rapid maneuvers [7]. During maneuvering, streamlined bodies take on a large angle of attack relative to the mean flow, resulting in a cross sectional profile that is no longer streamlined, but similar to a bluff body. Because of this change in profile, helical vortices are shed from the vehicle, resulting in strong regions of low pressure near the body, as seen in figure 1.

The presence of helical vortices, and their subsequent low pressure regions, near a body result in a large additional drag force on the vehicle during maneuvers. For a survey vehicle conducting a ‘lawnmower’ search pattern, the additional drag at each maneuver can add up quickly, resulting in a reduced mission length. For an autonomous vehicle, battery life and mission endurance are the driving factors for cost, and the amount of usable data collected. If vehicle drag can be reduced through the use of active sensing and control through maneuvers, the benefit to ocean data collection would be significant [7].

1.3. MEMS pressure sensor array requirements

While previous experimental works within the MEMS pressure sensor group [5, 7, 6, 8] used commercial off the shelf (COTS) pressure sensors, these sensors do not meet all of the requirements of the MEMS pressure sensor arrays currently under development. Of primary importance in the development of the MEMS pressure sensor arrays was the creation of a flexible and waterproof sensor array that could be surface mounted on a curved body, such as the hull of an underwater or surface vehicle. Additionally, it was desired to fabricate arrays of sensors that will ultimately mimic full body-length coverage of the fish lateral line [5].

The experiments conducted by Fernandez [5, 7], Dusek [8], and Maertens [6], utilized Honeywell 19mm...
series pressure sensors for measuring surface pressure. The Honeywell sensors were found to have excellent robustness and sensitivity, but their large size (30 mm height, 19 mm diameter), and lack of waterproofing made surface mounting the sensors impossible. Instead, the sensors required mounting inside a waterproof housing [5, 7], or mounting above the water surface, with pressure transmission tubes needed to transmit signals from the body surface to the sensors [8, 6]. In both cases, the size and water sensitivity of the sensors placed limitations on both the number of sensors that could be mounted on a body, and the size and shape of the experimental setup.

On the basis of experience gained from these previous experimental studies, particular emphasis was placed on optimizing the flexibility and waterproofing of the MEMS pressure sensor arrays. Ultimately, it is desired to produce sensor arrays with sufficient flexibility, waterproofing, and robustness to allow for surface mounting on a wide variety of surfaces without the need for altering the sensing body in any permanent way. To achieve this goal, innovative, flexible, material sets were chosen for the fabrication of the MEMS sensor arrays.

2. Experimental pressure sensor arrays

Within the MEMS pressure sensor group at the Center for Environmental Sensing and Modeling (CENSAM), several sensor technologies are currently under development. During January of 2012, three experimental sensor types were tested both in the CENSAM testing tank, and on an autonomous surface vehicle (ASV) at the Pandan Reservoir in Singapore. While the three sensors were based on different technologies, all three were flexible, waterproof, and able to be surface mounted on the vehicle. Two of the sensor arrays were developed around a silicon piezoresistive sensor die, discussed in section 2.1.1, and their individual packaging schemes will be discussed in sections 2.2.1 and 2.2.2. The field testing results for the two packaging schemes will be discussed together in section 5.4. The third sensor array was developed using an innovative conductive polymer material set, and will be discussed in section 2.4. While much work remains for further optimizing each sensor, initial trials beyond the laboratory environment showed great promise.

2.1. Silicon piezoresistive sensors

2.1.1. Pressure sensor dies. For the two pressure sensor arrays developed at the Nanyang Technological University (NTU) in Singapore, commercially available pressure sensor dies were implemented using two different packaging schemes to create flexible and waterproof sensor arrays. Piezoresistive-based absolute silicon micromachined pressure sensor dies (Model MS7201-A2 from Measurement Specialties Inc.) were chosen as suitable for deployment in harsh environments due to the construction of the pressure port from glass and silicon that is stable in most chemicals. Applied pressure was converted into electrical signal by the implanted piezoresistors in the silicon membrane, with packaging needed to provide the sensor die power and transport the output signal off-array. Other features included 0–100 kPa range, output span of 110 mV at 5 V supply voltage, temperature range from −40° to 150°C, small die size (1.35 × 1.79 mm²), affordability, and high reliability.

2.1.2. The underwater packaging scheme. A liquid crystal polymer (LCP) substrate was used, on which chromium (Cr)/gold (Au) electrical circuits were sputtered so that electrical connection via wires could be established with the bonded pressure sensor dies. Advantages of the LCP substrate included extremely low moisture absorption, superior hermetic sealing, and excellent chemical resistance. Thus, the substrate was able to maintain stable electrical, mechanical, and dimensional properties in wet, humid environments [9]. The most flexible method for processing LCP is the micromachining technique, as it is compatible with most photoresist. As a result, standard IC fabrication processes, such as photolithography, etching, and metallization, can be utilized to process the LCP substrate. As a complement to the LCP substrate, a flexible printed circuit board (PCB) substrate was also implemented to attach the sensor dies. For waterproofing and sealing purposes, polydimethylsiloxane (PDMS; or silicone rubber) was dispenses over the LCP and flexible PCB substrates. These LCP/PDMS and flexible PCB/PDMS combinations resulted in flexible pressure sensor arrays that could be easily deployed on the streamlined bodies of marine vehicles.

2.2. Fabrication

2.2.1. The LCP/PDMS packaging scheme. For the LCP/PDMS packaging scheme, the processing of two LCP substrates was involved: (1) the sensor and (2) the base. For the sensor substrate, the fabrication process consisted of five steps. First, a square copper (Cu) feature (2 mm × 2 mm) was patterned on the LCP substrate by photolithography and Cu etching. Subsequently, this Cu pattern defined the location of a mechanically drilled through-hole (diameter 1.2 mm) in the substrate. Second, a metallic layer of Cr (30 nm)/Au (700 nm) was sputtered onto the LCP substrate to form the electrical circuits for the sensor dies. Third, a through-hole was drilled through the LCP substrate via the Cu pattern so that the sensor’s back-face pressure port could be accessed by water. After that, any residual Cu pattern around the through-hole was etched away. In the fourth step, after cutting out the individual sensor substrates, the sensor die was bonded to the LCP substrate using adhesive with the alignment performed under a microscope. Finally, the sensor die was wire-bonded to the Cr/Au electrode pads using Au wires. For additional mechanical protection, the entire sensor die, together with the bonded wires, was encapsulated in silicone gel. These fabrication steps resulted in a sensor module ready to be placed on the LCP base substrate during the assembly process.

For the base substrate, the fabrication process consisted of three steps, which were similar to those of the sensor substrate. For the assembly of the sensor modules to the base substrate, four steps were involved. First, the sensor modules
Figure 2. Fabricated pressure sensor array (2 × 5) with the LCP/PDMS packaging scheme. Size: 65 mm × 40 mm and sensor pitch: 10 mm (x-direction) and 8.5 mm (y-direction). (a) A completed LCP sensor array before encapsulation. (b) The back face of an encapsulated LCP array.

Figure 3. Fabricated pressure sensor array (2 × 10) with the flexible PCB/PDMS packaging scheme. Size: 40 mm × 20 mm and sensor pitch: 3 mm (x-direction) and 5.5 mm (y-direction). (a) The back face of an encapsulated PCB sensor array. (b) The front face of an encapsulated PCB sensor array.

were bonded to the LCP base substrate using adhesive with the alignment performed under a microscope. Second, individual wires and ribbon cable wires were hand-soldered on the sensor modules and the base substrate to complete the electrical circuits. Where necessary, Ag conductive epoxy was used in addition to solder to enhance the durability of the electrical connections. Third, after securing the LCP base substrate (with assembled sensor modules) to a container, PDMS was dispensed over the whole assembly and subsequently allowed to cure at room temperature. Figure 2 illustrates the fabricated pressure sensor array.

2.2.2. The flexible PCB/PDMS packaging scheme. For the flexible PCB/PDMS packaging scheme, the fabrication process consisted of similar steps to the LCP/PDMS array one. First, the sensor die was bonded to the flexible PCB substrate using adhesive with the alignment performed under a microscope. Second, the sensor die was wire-bonded to the Au electrode pads using Au wires. For additional mechanical protection, the entire sensor array was encapsulated with silicone gel. Third, ribbon cable wires were hand-soldered on the flexible PCB substrate to complete the electrical circuits. In the fourth step, after securing the flexible PCB substrate to a container, PDMS was dispensed over the sensor array and subsequently allowed to cure at room temperature. Figure 3 illustrates the fabricated pressure sensor array.

2.3. Hydrostatic calibration

Prior to deployment of the experimental pressure sensors on a streamlined body, hydrostatic calibration was performed in the laboratory. The piezoresistive sensor dies used in both the
Figure 4. Multi-step hydrostatic calibration results for the LCP/PDMS packaging scheme. During testing, array channels 5 and 7 were not operational due to the pressure access hole on the back face of the sensor being blocked by protruding edges of LCP substrate created during the manual drilling of the access holes. The noise present in the sensor output signal was attributed to the use of unshielded cables between the sensor and the NI DAQ used for data collection. A further discussion of the signal noise can be found in figure 13 and section 5.4. (a) Example calibration for the bottom row of the LCP sensor array. (b) Sensor calibration plot for the LCP/PDMS packaging scheme with an average sensitivity of 0.99 µV Pa\(^{-1}\) with a 5 V supply voltage.

Figure 5. Multi-step hydrostatic calibration results for the flexible PDMS packaging scheme. (a) Multi-step hydrostatic calibration results for the flexible PCB/PDMS packaging scheme. Only six channels are shown due to limitations in data acquisition. The operation and calibration of the remaining channels were independently verified. (b) Sensor calibration plot for the flexible PCB/PDMS packaging scheme with an average sensitivity of 0.92 µV Pa\(^{-1}\) with a 5 V supply voltage.

LCP and flexible PCB packaging schemes operated on the principle of the Wheatstone bridge, and a 5 V input voltage was used during calibration with the sensor output voltage recorded using a National Instruments Data Acquisition Board (Model USB-6281) and Labview software. Hydrostatic calibration was performed by placing the sensor arrays at known depths in the CENSAM testing tank, and acquiring the output signal over a 60 s period. Both sensors performed as expected, producing a linear relationship between pressure and output voltage with negligible hysteresis, as seen in figures 4(b) and 5(b).

2.3.1. The LCP/PDMS packaging scheme. Figure 4 illustrates the voltage data acquired by the DAQ system in the time domain during the multi-step hydrostatic calibration of the LCP/PDMS sensor. The left half of the plots shows the stepwise increase in the hydrostatic pressure when the sensor array was lowered into the water tank while the right half shows the stepwise decrease in pressure when the sensor array was raised upwards. From figure 4, a sensor calibration plot could be obtained as shown in figure 4(b). As illustrated, the average sensor sensitivity is about 0.99 µV Pa\(^{-1}\) with a 5 V supply voltage. During testing, it was found that sensor channels 5 and 7 produced unreliable results due to an air bubble forming at the hole giving access to the sensor die, preventing water from reaching the sensing membrane. The formation of this bubble was likely due to the presence of protruding edges of LCP in the access hole, created during the manual drilling of the LCP substrate. Although deep reactive ion etching recipes were developed that could etch LCP, the etch rate was found to be too low, and etching of the mask layer was experienced in some cases. Because the pressure die access holes were large enough for manual drilling, this technique was employed with generally favorable results.
2.4. The conductive polymer pressure sensor

The third pressure sensor array deployed on the ASV was developed at the Massachusetts Institute of Technology (MIT), and fabricated entirely from a polymer. Unlike the silicon piezoresistive pressure sensors that employed rigid dies on a flexible backing, the polymer-based sensor was completely flexible. The active part of each sensor cell in the array was a strain-concentrating diaphragm molded from polydimethylsiloxane (PDMS), on which a piezoresistive strain gage was patterned [10, 11], as seen in figure 6. A pressure difference across the diaphragm caused it to deflect, and this deflection was transduced by the strain gage. PDMS was chosen as the sensor material because its favorable chemical resistance and waterproofing characteristics are desirable for long term underwater usage. Additionally, its flexibility allows the sensor array to be compatible with the streamlined bodies of underwater vehicles, making it amenable to wide-area fabrication and deployment. The strain gage was made of PDMS doped with carbon black. This composite was chosen because it is inexpensive, compatible with the main body of the sensor array, highly piezoresistive [10, 11], and provides for repeatable operation.

Figure 6 illustrates the voltage data acquired by the DAQ system in the time domain during the multi-step hydrostatic calibration of the flexible PCB/PDMS sensor. The plot shows the stepwise decrease in the hydrostatic pressure when the sensor array was raised upwards in the water tank. From figure 5(a), a sensor calibration plot could be obtained as shown in figure 5(b). As illustrated, the average sensor sensitivity is about 0.92 \( \mu \)V Pa\(^{-1}\) with a 5 V supply voltage.

2.3.2. The flexible PCB/PDMS packaging scheme. Figure 5(a) illustrates the voltage data acquired by the DAQ system in the time domain during the multi-step hydrostatic calibration of the flexible PCB/PDMS sensor. The plot shows the stepwise decrease in the hydrostatic pressure when the sensor array was raised upwards in the water tank. From figure 5(a), a sensor calibration plot could be obtained as shown in figure 5(b). As illustrated, the average sensor sensitivity is about 0.92 \( \mu \)V Pa\(^{-1}\) with a 5 V supply voltage.

2.3.3. Hydrostatic calibration analysis. Although the LCP/PDMS and PCB/PDMS packaging schemes employed the same commercially available piezoresistive sensor dies from Measurement Specialties, the sensitivities of the two sensor arrays were found to differ by approximately 7%. The difference in measured sensitivity can primarily be attributed to two factors. The first was experimental errors occurring when performing the multi-step hydrostatic calibration in the CENSAM testing tank. Although great care was taken in placing the two sensor arrays at the same depth, small errors in the measured versus actual depth of submersion could lead to differences in the measured sensitivity. Differences in array sensitivity could also be attributed to stresses generated on the piezoresistive sensor dies as the PDMS cured. The thickness of the PDMS encapsulation on the two sensor arrays was not identical, creating the potential for different stresses on the sensor dies as the PDMS dried.
The conductive polymer sensor array was composed of four individual sensor diaphragms, each employing a PDMS–carbon black strain gage as the sensing element. (a) Side view of the polymer-based pressure sensor array showing the sensor diaphragms with 1 mm material thickness and 2 mm air cavity. The $1 \times 4$ array had a sensor pitch of 25 mm ($x$-direction). (b) Top view of the polymer-based pressure sensor array showing the Kelvin-probe structure used to measure the voltage across each strain gage without the influence of contact resistance. Each sensor diaphragm had a material thickness of 1 mm, with a 2 mm air cavity. The screen-printed carbon black/PDMS strain gages had a thickness of 100 $\mu$m.

Pressure sensor output recorded during an open-water kayak test. The pressure recorded by a polymer-based sensor is shown in green, with the Honeywell SPT series sensor in blue. During the kayak experiments, the polymer-based sensor demonstrated a sensitivity of 1.21 $\mu$V Pa$^{-1}$ with a 12 V supply voltage. It was observed that the polymer-based sensor captured the same trends as the commercial sensor during the experiment.

Figure 9. An autonomous kayak, used in radio control mode, was used as a platform for testing multiple arrays of experimental pressure sensors.

To demonstrate the capabilities of the polymer-based pressure sensor array, one array was mounted on the hull of a kayak, and its pressure signals were recorded during kayak maneuvers in the Pandan Reservoir. For reference, the kayak hull was also instrumented with commercial pressure sensors at nearby locations. This experimental setup is discussed further in section 3. Figure 8 shows two pressure signals recorded during one kayak maneuver. The pressure measured by a commercial sensor is shown in blue, and that measured by a polymer-based sensor is shown in green. During the kayak experiments, the polymer-based sensor demonstrated a sensitivity of 1.21 $\mu$V Pa$^{-1}$ with a 12 V supply voltage. Note that to create figure 8, the pressure signal from the polymer-based sensor has been shifted in time so as to best match the pressure signal from the commercial sensor; again, the two sensors were not co-located. The figure shows that the pressure response of the polymer-based sensor was similar to that of the commercial sensor, demonstrating the promising functionality of the polymer-based sensor in uncontrolled conditions.

3. The autonomous surface vehicle

In order to test the experimental pressure sensors outside the laboratory environment, an autonomous surface vehicle, operated with radio control, was employed. Based on a Pungo 100 rotomolded kayak (from Wilderness Systems), the vehicle provided a platform capable of carrying multiple experimental pressure sensor arrays, along with a suite of commercial pressure sensors and vehicle navigation instrumentation, as seen in figure 9.

The kayak was equipped with two onboard computers within a custom waterproof electronics box. One computer
was responsible for the control of the kayak’s onboard sensors which include a digital compass, GPS, IMU, and DVL. This computer ran Ubuntu Linux, and was loaded with MOOS-IvP software which managed both the data collection and saving, and could provide for autonomous operation if desired (for more information on the MOOS-IvP software, please see www.moos-ivp.org).

The second onboard computer ran a Windows operating system, allowing for the use of National Instruments Labview software to be employed for collecting data from the commercial pressure sensor suite and the experimental pressure sensors. Labview provided an easy to use interface for collecting data from a large number of sensors, while also allowing visual inspection of the signals in real time, enabling the operation of each sensor to be verified before deployment.

4. Commercial pressure sensors

In order to provide a baseline against which to test the experimental pressure sensors, the kayak was outfitted with 19 Honeywell SPT series pressure sensors. Honeywell 19mm pressure sensors had been used in previous experiments by group members, and were found to be both sensitive and robust. The SPT series sensors offered similar sensitivity and robustness to the previously used sensors, while also carrying onboard amplification, allowing for easier implementation in the bow compartment of the kayak. The SPT series sensors were individually calibrated before use, and were found to have excellent consistency in both voltage offset and calibration constant. To reduce the measurement noise from the SPT sensors, a first-order RC filter was used between the sensors and the National Instruments Data Acquisition Board (Model USB-6281).

While the SPT sensors were found to provide an excellent baseline for verifying the performance of the experimental sensor arrays, the size of the sensors (73 mm height, 22 mm diameter) was substantially larger than desired for surface-mounted applications. Because of their size, mounting the sensors to the kayak was substantially more difficult than setting up the experimental arrays. While the flexible PDMS encapsulated arrays were adhered directly to the exterior of the kayak hull using silicone adhesive, the Honeywell SPT sensors were mounted on the interior of the kayak bow section by threading the individual sensors into tapped Delrin blocks that were epoxied to the kayak inner hull. Holes were drilled through the kayak hull at each sensor location, allowing for the surface pressure to be measured, but also introducing potential failure points to the kayak system.

5. Field experiment results

Two series of experiments were conducted using the autonomous surface vehicle outfitted with experimental surface-mounted pressure sensor arrays. The first series of experiments were conducted in a pool at the National University of Singapore (NUS), allowing for simple and controlled vehicle motions without the influence of waves or the vehicle’s thruster. The second series of experiments were conducted at Singapore’s Pandan Reservoir, and allowed for the sensor arrays to be tested in ‘real world’ operating conditions.

5.1. Pool experiments

Before taking the kayak vehicle to Singapore’s Pandan Reservoir, experiments were conducted in one of the swimming pools at NUS to ensure the operation of the pressure sensors, as well as remote data collection from the vehicle.

Because the pool at NUS was limited in size, experiments were restricted to simple vehicle motions that did not use the vehicle’s propulsor. Unfortunately, the conductive polymer-based sensors were not working during the initial pool tests due to an electrical problem that was remedied before conducting experiments at the reservoir. The two silicon piezoresistive sensors were found to be working, however, and responded well to various vehicle motions.

5.1.1. The roll test. A roll response test was performed by forcing an oscillatory roll motion by hand in the pool. Because the silicon piezoresistive sensors were mounted on opposite sides of the vehicle, it was expected that the signals from the two sensors would be 180° out of phase, as seen in figure 10(a). The voltage output from the silicon piezoresistive sensors was found to have high frequency noise of approximately 25% of the signal magnitude, but a Butterworth filter at 20 Hz greatly improved the output signal, as seen in 10(a).

To verify the time response of the sensors, the frequency spectrum of the sensor response, seen in figure 10(b), can be compared to the roll motion from the IMU data, as seen in figure 11.

It was observed that the primary 1 Hz frequency of the sensors matched the roll frequency, demonstrating that the sensors were working as expected. The frequency response of the pressure sensors also contained a 1.75 Hz component which was not observed in the frequency response of the roll motion from the IMU data. It was concluded that this higher frequency component could be attributed to the sensors temporarily leaving the water during the extremes of the roll motion, as observed in the flattening of the top of the pressure spikes in figure 10(a). Similar experiments were performed for the case of pitch and yaw, each with results matching expectations.

5.2. Pandan Reservoir experiments

Experiments were conducted at Singapore’s Pandan Reservoir on 25 and 26 January, 2012 to verify the operation of the experimental arrays in ‘real world’ conditions. Pandan Reservoir is located in the southwest portion of Singapore, and is a drinking water reservoir managed by the Singapore Public Utilities Board. Located near the Singapore–MIT Alliance for Research and Technology (SMART) center at NUS, the reservoir offers an ideal setting for the testing of underwater and surface vehicles.
A roll test was performed in the NUS pool to test the response of the experimental sensor arrays. (a) A roll test was performed on the kayak in the NUS pool. The two silicon piezoresistive sensors reacted as expected, with periodic signals 180° out of phase. Variation in peak magnitude between channels could be attributed to a slight difference in depth below the kayak waterline between the PCB and LCP arrays. (b) Power spectrum for the silicon piezoresistive sensors during the pool roll experiment. Strong frequency components are observed at approximately 1 and 1.75 Hz. The variation in power spectral density between the two arrays was due to differences in mounting position, and a slight difference in sensitivity between the LCP and PCB arrays.

The kayak inertial motion unit (IMU) was used to measure the vehicle’s roll angle and verify the frequency response of the sensors. (a) A time series of the kayak roll angle from the IMU during tests in the NUS pool show a periodic roll motion with a maximum amplitude of approximately 15°. (b) Power spectrum for the IMU roll data during the pool roll experiment showing that the roll motion of the kayak was forced at approximately 1 Hz.

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

For the experiments at Pandan, the problems of electrical connection to the conductive polymer sensors had been resolved, enabling all of the sensors on the kayak to be used simultaneously. To ensure that the conductive polymer sensors were operating as expected, the roll and pitch experiments without the thruster were repeated at the reservoir. It was found that for both the roll and pitch experiments, all three sensor types (commercial, conductive polymer, and silicon piezoresistive) worked as expected, as seen in figures 12(a) and (b). The commercial sensors gave the largest signal due to their onboard amplification, but the periodic vehicle motions could be easily identified in the signals from the experimental sensors of both types. In the cases of both experimental sensor types, the signal-to-noise ratio was not as good as for the commercial sensors, revealing an area to be addressed in future iterations of the sensors.

5.3. Self-propelled experiments

One of the primary goals for the Pandan Reservoir trials was to test the sensors in ‘real world’ operating conditions. While simple vehicle motions without the thruster demonstrated that the sensors were working as expected, the successful implementation of the sensors on a self-propelled vehicle was considered a crucial proof of concept of the utility of pressure sensors as a feedback mechanism on marine vehicles.

Self-propelled tests of several types were conducted at the reservoir, all with the intention of producing strong
Unpowered experiments were repeated at Pandan after the problems of connection with the conductive polymer sensors were fixed. Only operational channels from the sensors arrays are shown, and an 80-point moving average was applied to the experimental data. (a) The unpowered roll test was repeated at the reservoir to ensure the operation of all three pressure sensor types. (b) The unpowered pitching experiment was repeated at Pandan.

During the experiments at the Pandan Reservoir, it was found that operating the thruster added significant noise to the silicon piezoresistive sensors. In the figure above, the thruster was enabled at approximately 12 s. The increase in noise was not experienced when the thruster was operated in air. It is believed that noise was introduced to the signals through the unshielded ribbon cable used between the sensor arrays and the NI DAQ board. Work is ongoing to incorporate filtration and amplification onboard the sensor arrays, as well as using shielded components to mitigate the effects of external noise. Two channels of the PCB/PDMS sensor were damaged during transport of the kayak to the Pandan Reservoir and are not plotted.

Hydrodynamic signals for the sensors to detect. Unfortunately, one result that was immediately apparent during the experiments was the noticeable increase in noise on the silicon piezoresistive sensors when the thruster was in operation, as seen in figure 13. The increase in noise was not observed when the motor was tested in air, and the magnitude of the increased noise was found to make discerning hydrodynamic signals difficult.

Circle maneuvers were performed to both port and starboard in order to investigate whether the pressure sensors could be used to measure the drift angle of the vehicle. Previous experiments using a sailboat hull equipped with commercial pressure sensors and towed at various angles of attack showed that a nearly linear relationship existed between the pressure difference across the bow of the vehicle, and the angle of attack [7]. It was believed that by conducting circle tests at various radii, the drift angle found from compass and GPS data could be compared to pressure measurements, and a similar relationship established.

Interpreting the results from the self-propelled kayak experiments was complicated by the data collection system employed on the kayak. Because navigational and pressure data were recorded on two separate computers, relating features in the pressure signals to vehicle motions required special care. In the case of the circle test, coordinating the pressure and navigational data was accomplished by comparing features in the pressure data recorded using the commercial sensors, and the vehicle roll motion found from the IMU. The unpowered roll experiments in figure 11 showed that the pressure sensors were well-suited for measuring the vehicle roll dynamics, verifying the utility of roll data as a means for coordinating pressure and navigational data. For the circle test in figure 14, the time difference between the navigation and pressure data was found to be approximately 20 s.

Considering a port circle experiment, seen in figure 14(a), all three sensor types showed an initial drop in voltage, followed by a rise to a steady value that was maintained for the remainder of the experiment. By comparing the pressure during the first 20 s of the turn with the yaw rate and acceleration, it was found that the pressure sensors showed a measurable change in pressure during the initiation of the port turn, when the yaw rate was changing and the acceleration was non-zero, as seen in figure 14(b). When the vehicle reached a steady yaw rate, the pressure recovered to a steady value, and remained constant for the remainder of the turning maneuver.

In addition to the variation in pressure during the unsteady portion of the circle maneuver, oscillations in the 0.75–1 Hz range were present in the pressure signals, as seen
Figure 14. Pressure and navigational data were recorded during a circle to port in the hope of evaluating the vehicle drift angle. It was found that the initiation of a turning maneuver resulted in a dip in pressure while the turning rate remained unsteady. When a constant turning rate was achieved, the pressure recovered to a near-steady value for the remainder of the circle. (a) During the port circle experiments, a dip in pressure was observed during the initiation of the turn, followed by a constant value during the remainder of the maneuver. Two channels from each sensor were chosen for clarity, and an 80-point moving average was applied to each signal. (b) The vehicle yaw angle, rate, and acceleration were found from IMU data. From the IMU data, it was observed that the turn to port was initiated at approximately 0 s, with a steady turning rate achieved by approximately 6–7 s.

Figure 15. The frequency content of the commercial pressure sensor data and the kayak roll motion were compared to ensure that the oscillations in the pressure data could be attributed to the small amplitude kayak roll motion during the maneuver. (a) The power spectrum for the commercial sensors during the port circle maneuver revealed the presence of oscillations in the range of 0.75–1 Hz. (b) The power spectrum of the IMU roll data showed that the roll motion had the same frequency range as the oscillations in the commercial pressure sensor data.

in figure 15(a). These oscillations were present whenever the vehicle was undergoing a turning maneuver, and were caused by a small amplitude, but constant frequency, rolling motion of the kayak, as seen in figure 15(b).

Additional self-propelled experiments conducted with the kayak vehicle consisted of circles to port and starboard, zigzag motions in both forward and reverse, and passes in close proximity to a stationary pier. In each case, the vehicle pitch and roll dynamics were clearly evident in the pressure data, but larger flow structures were more difficult to distinguish. These results suggest that additional optimization of sensor design is needed before the existing sensor arrays can be implemented as a feedback mechanism on an operational vehicle.
5.4. The silicon piezoresistive sensor analysis

The silicon piezoresistive sensors have two main areas where improvement is needed: packaging size and signal-to-noise ratio. While both the PCB-based and LCP-based arrays are contained in a very small, flexible strip, the PDMS encapsulation is too large for practical application. In order for the MEMS sensors to be a viable feedback solution on a variety of marine vehicles, the sensor arrays must be robust, easy to apply, and small enough not to alter the near-body flow field. To meet these goals, the size of the encapsulated sensors must be reduced.

The signal-to-noise ratio is also an area where improvement is needed for the silicon piezoresistive sensors. While the sensors produced a measurable signal without amplification, operating the thruster created noise that nearly masked the desired signal, as seen in figure 13. In an effort to resolve the signal-to-noise ratio of the silicon piezoresistive sensors, work is under way to incorporate a low-pass filter and amplifier onto the same strip as the sensor dies, creating an array that requires no external circuitry and delivers a strong signal-to-noise ratio. This design change will retain the flexibility and size benefits of the current sensor, while enhancing the usability of the output signal.

5.5. The conductive polymer sensor analysis

The conductive polymer sensors demonstrated mixed results when tested on the surface of the kayak. The implementation of the sensors was straightforward, with the completely flexible sensors able to be mounted at any location on the kayak’s hull. Additionally, it was found that the sensor arrays could be powered with either a 0 V reference or a −12 V reference, allowing them to be connected to the same set of batteries as the commercial pressure sensors.

Where the conductive polymer sensors struggled was in sensitivity compared to both the commercial and silicon piezoresistive sensors. During the testing of the sensors, the conductive polymer output signals were found to be on the order of millivolts, even after amplification. As a consequence of the small amplitude response of the sensors, small variations in pressure were not detected by the array, or masked by noise. Enhancing the sensitivity of the sensor array would improve its utility as a feedback mechanism for a marine vehicle where relevant flow structures produce pressure variations on the order of tens to hundreds of pascals.

Additionally, the question of back pressure on the conductive polymer sensor array remains an open, and relevant, question. During the experiments on the kayak vehicle, a reliable way to maintain a constant back pressure on the sensors was not achieved. In order to reliably measure pressure, the back pressure needs to be held constant, or the baseline calibration of the sensors will be in constant flux. While this requirement presents an engineering design and fabrication challenge, work is under way to resolve the issue using a microchannel patterned into the sensor substrate that will account for variations in hydrostatic pressure.

6. Conclusions

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

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

Overall, the experiments conducted during January 2012 served as an important proof of concept for the experimental MEMS pressure sensor arrays. All three experimental arrays demonstrated the ability to measure dynamic pressure while mounted on the curved kayak hull. In addition, the sensors were shown to deliver a measurable signal, despite suffering from additional noise while the thruster was in operation. Although experiments demonstrated significant progress from previous generations of the sensors, they also revealed areas where improvement was needed for each sensor type.

7. Future work

While the existing experimental sensor arrays were successfully mounted on a marine vehicle and demonstrated their ability to measure vehicle dynamics, work is ongoing both on the physical sensor arrays, and on the hydrodynamics of maneuvering vehicles. The primary goal of the continued sensor array development is to improve the robustness and signal-to-noise ratio. As has been previously discussed, all of the experimental sensor arrays suffered from signal-to-noise problems when the vehicle motor was in operation. In addition, the sensor robustness was a cause for concern when transporting the kayak vehicle from the NUS campus to the Pandan Reservoir. While the sensor arrays survived normal operating conditions very well, several individual sensor dies from the piezoresistive arrays were damaged when the kayak was improperly placed on its transport cart during deployment. For the future, it would be desirable for the sensor arrays to be a ‘stick and forget’ technology, and design changes to allow for this vision are currently under development.

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