Goal: To design, develop, and fabricate a sensor array for the identification of hydrodynamic stimuli, particularly object shapes and wake structures.

Background:
This research is directly inspired by the lateral line organ, found in all fish and responsible for many interesting behaviors. The lateral line organ measures fluid flow velocity and pressure gradients on the surface of the fish. The canal system, which measures pressure gradients, has been found experimentally to be responsible for:
- Tracking prey by wakes.
- Locating prey in dark or murky water.
- Schooling (in conjunction with other sensory systems such as sight).
- Imaging unknown objects passively and actively.
- Minimizing energy expenditure by utilizing vortex streets.

A similar sensory system would provide great benefits to ships and AUVs. Such a sensor would be inherently low power and passive. Many of the biological behaviors observed with the lateral line would translate into welcome capabilities for underwater vehicles.

In particular, an artificial lateral line would allow the imaging of objects based solely on their fluid interaction, as well as object avoidance and control optimization.

An artificial lateral line sensor array would be limited in practical range to approximately 2-3 times the array length. However, it would provide detailed information about surroundings in environments where sonar and vision systems fail.

The two main components of this research are:
- To design and fabricate a bio-inspired sensor array which is capable of measuring the same relevant data as the lateral line. This has to lead a focus purely on the pressure measurements, based on biological characterizations of the lateral line.
- To develop algorithms for the identification and location of hydrodynamic stimuli based on measurements available through the lateral line.

Estimation: Object Identification
If the shapes of objects is known a priori, then a tailored-made method may be used to sort or identify the objects. An experiment was performed using 4 off-the-shelf pressure sensors in a linear array, in which cylinders of square or round cross sections were identified from the pressure as they passed the sensors. Cylinders arrangements of variable cylinder size, flow velocity, and distance to the sensors were used. A Principal Component Analysis (PCA) was performed to arrive at a linear classifier to score individual traces (based on the first three principal components). The classification error rate was 1% across all the sizes, speeds, and distances.

Estimation: Vortex Strength and Position
Vortices are important in our sensing scheme for what they reveal about the objects that generated them and for their effects on control surfaces and bodies. Here the same pressure sensors are used to estimate the position and strength of hand-generated vortices. Filtered data is used in a sequential estimation approach based on a potential flow model to obtain the estimate. First the vortex strength which minimizes a least squares cost function is identified on each point of a grid. The map of minimum cost depicts the most likely position of the vortex and the certainty of the estimate.

Estimation: Mapping Arbitrary Objects
Mapping out the shape of a completely unknown object requires the determination of infinitely many parameters. Dr. Bouffanais et al. have provided an intuitive ordering of the problem parameters through a conformal map from a unit circle into an arbitrary shape:

\[
g(z) = -\alpha - \sum_{k=0}^{\infty} \frac{1}{k!} \sum_{m=0}^{k} \frac{1}{2^m} \sum_{n=0}^{m} \binom{k}{m} \binom{m}{n} \binom{m}{n} \binom{2n}{m} \binom{2m}{n} \binom{2n}{m} \binom{2m}{n} \cdots
\]

\[\mu_n\] provides a (n+1)-polygonal perturbation to the shape, and the contribution to the flow decays as distance to the \(n=1\) power.

In potential flow, the shape parameters can be estimated from pressure measured a constant radius from the object by minimizing a modified least squares cost function in which the parameters are weighted by the radius to the corresponding power.

Sensor Array Design and Fabrication
The pressure sensor array design, seen at left, consists of a series of 20 µm thick square silicon membranes flush with the external flow and with a common backplane. The membranes are 2mm in size. The array is being fabricated using MEMS technology. The design objectives are 1 Pa resolution over a range of 10 kPa with 4 mm resolution.

The pressure is measured through the deflection of the membrane, by way of a metal strain gauge on the surface of the membrane. Four resistors compose the elements of the strain gauge (seen at right) which are combined in a Wheatstone bridge to improve sensitivity. The resistor paths were chosen to optimize sensor sensitivity.

Tests of individual sensors with a profilometer indicate that the deflection of the membranes behaves according to theory and is linear in the range measured (2mm and 2.8 mm diaphragms shown at left). Tests have also been performed of the resistors in the strain gauge. Shown here are results for a 2.8 mm diaphragm. The measured slope of the change in resistance against pressure was found to be twice the expected theoretical result.

Currently a submersible array with fully functioning sensors is completing fabrication.

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