2014

Bio-Inspired Flow Sensing for Underwater Guidance and Navigation

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1. Narrative

It is with sincerest gratitude that I am privileged to submit this final report reviewing the research I conducted with financial support from Link Foundation Ocean Engineering & Instrumentation Ph.D. Fellowship program. Monetary support from the Link Foundation assisted in allowing me to complete the final phase of my doctoral program and positively impacted my research in bio-inspired sensing and control for autonomous underwater vehicles.

The outline of this report is as follows. The introduction provides a general overview of my research project in bio-inspired sensing and control, specifically overviewing the central objectives of the project, background information, and related work. The results sections summarize theoretical and experimental accomplishments achieved during the project. The final sections describe the significance and impact of this work as well as suggestions for future research.

Introduction

Stream-dwelling fish and aquatic mammals have an innate ability to navigate often-tumultuous environments with impressive precision, a highly desirable trait for underwater vehicle applications. For example, trout use their lateral line to sense vortices shed by an upstream obstacle and slalom between the vortices to reduce energy expenditure compared to free-stream swimming [3]. Moreover, harbor seals can use their whiskers to follow the trail of flow disturbances created in the wake of an object that has passed minutes before [4]. Recent developments in materials science have produced sensors that can measure local flow velocity similar to seal whiskers, and integration of this sensing modality may enhance the navigation abilities of underwater vehicles beyond traditional means. The goal of this project was to assimilate measurements from a bio-inspired, multi-modal sensor array composed of local flow velocity sensors and pressure sensors to improve the guidance and navigation of underwater vehicles. Specifically, the theoretical and experimental aims of the project include 1) to derive estimation algorithms that assimilate measurements from a multi-modal, bio-inspired sensor array to allow an underwater vehicle to estimate the size and position of an obstacle based on the properties of the wake it produces, 2) to derive control algorithms steering the vehicle to station-holding behavior in which the vehicle holds its position behind the obstacle, and 3) to validate theoretical results by creating an underwater testbed in a stream-like environment.

Within the context of current activities in the field, this work incorporates local *flow velocity* and *pressure gradient* measurements, creating a multi-modal, distributed sensor array to estimate properties of the fluid environment. Prior works have investigated using pressure gradient measurements for purposes including obstacle [5],[6] or vortex detection [5],[7], however, these methods assume a single sensing modality rather than a multi-modal array and did not incorporate feedback control using estimated properties of the environment.

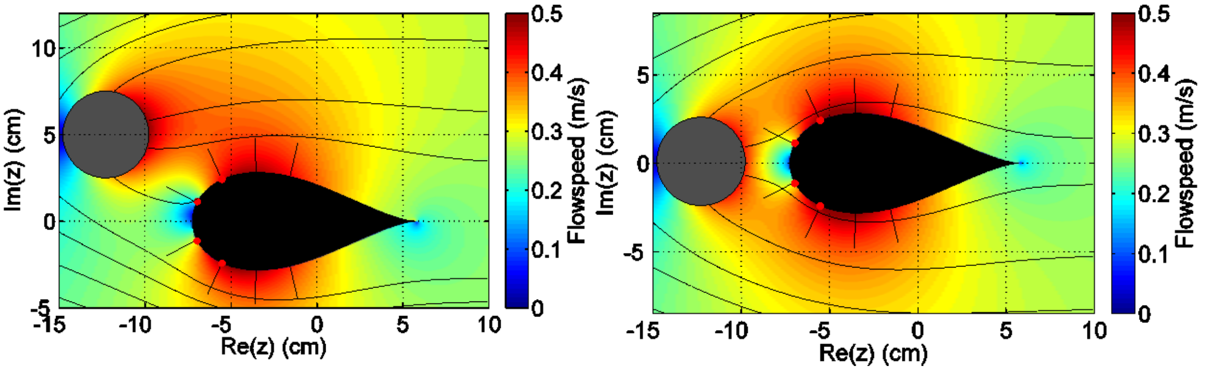
Theoretical Results

This project utilized tools from potential flow theory to model the fluid motion around a foil in the presence of an upstream obstacle. Potential flow theory is advantageous because it offers model simplicity; however, potential flow models often suffer from model error when compared to physical flows since they do not model viscous effects. The potential flow model facilitates calculation of the measurements one can expect from local flow velocity sensors and, when paired with Bernoulli's principle, pressure difference measurements from distributed pressure sensors. The theoretically predicted measurements are compared with actual measurements in a recursive Bayesian filter to estimate the size and position of the obstacle relative to the foil.

Using the theoretical measurements produced by the potential flow model and distributed sensor array, we implemented a recursive Bayesian filter to assimilate the measurements and estimate the relative position and size of the obstacle. The recursive Bayesian filter assigns a probability density to a candidate estimate based on measurements taken from multiple sensors. In this work, we assume the candidate estimate with the largest probability is the best estimate at a given time. This project incorporated eight local flow velocity sensors and four local pressure sensors. A key benefit of the recursive Bayesian formulation is that it assimilates measurements in both space and time, using previously collected data and current measurements to improve the overall estimation performance. An additional benefit is its ability to fuse data from multiple noisy sensors modalities. Fusing the two modalities (flow velocity sensing and pressure difference sensing) results in more accurate estimation performance than would be obtained from either modality alone.

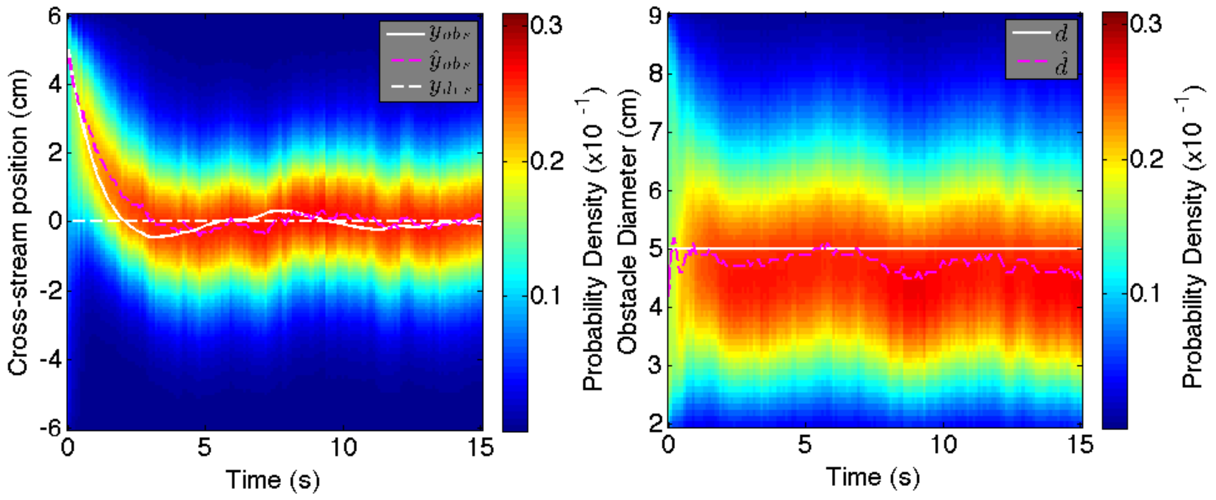
A key benefit of the multi-sensor, multi-modal artificial lateral line is its robustness to individual sensor or modal failure. Because of the distributed nature of the sensing array, failure of a single sensor will decrease estimation performance, but not inhibit operation. Likewise, loss of an entire sensing modality (e.g., all eight IPMC sensors or all four pressure sensors) will not inhibit operation of the estimation scheme – though it would decrease performance. Moreover, the recursive Bayesian approach allows non-symmetric and/or optimized sensor configurations.

For station-holding the control is designed using feedback of the estimated cross-stream obstacle position from the recursive Bayesian filter. Assuming that the vehicle is controlled by an overhead gantry system, we showed that using a proportional controller exponentially stabilizes the vehicle position behind the obstacle and position error is bounded by the control gain and magnitude of the estimation error.



(a)

(b)



(c) (d)

Figure 1. Simulation of estimation and feedback control for station-holding behind an obstacle. (a,b) The initial and final position of the foil; (c,d) marginal probability densities of the recursive Bayesian filter [2].

Figure 1 shows a discrete-time simulation of closed-loop station-holding using the estimated relative obstacle position in a proportional feedback controller [2]. Figures 1(a) and 1(b) show the initial and final position of the streamlined body relative to the obstacle, which is illustrated by the shaded circle. Figures 1(c) and 1(d) show the marginal probability densities of the cross-stream obstacle position and diameter. The actual obstacle position and diameter are depicted by the solid white lines; the parameter estimates are represented by a dashed magenta line. The position corresponding to station-holding (at zero cross-stream position) is illustrated by the dashed white line in Figure 1(c). Flow sensor positions are denoted by black lines protruding from the body in Figures 1(a) and 1(b), whereas pressure sensor positions are denoted by red circles. Note that the closed-loop estimation control algorithm steers the foil behind the obstacle, with estimation errors causing small deviations [2]. The recursive Bayesian filter also accurately estimates the obstacle diameter, as shown in Figure 1(d).

Experimental Results

As part of a collaborative effort[1] we designed and constructed a robotic fish prototype outfitted with eight ionic polymer metal composite (IPMC) sensors that are sensitive to local flow velocity and four embedded pressure sensors that produce six pressure difference measurements [1]. The robot prototype is a 3D-printed 2D-airfoil shape extruded in the vertical direction, as shown in Figure 2. The prototype is designed using a modular approach to 1) enable convenient installation and replacement of both IPMC and pressure sensors, 2) maintain flexibility in the number and placement of sensors around the foil, and 3) ensure a compact structure appropriate for its operating environment [1].

Above the IPMC sensor blocks, the foil has nine slots for mounting the pressure sensors, as shown in Figure 2 [1]. The pressure sensors are mounted above the IPMC sensor block to minimize fluid effects

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[1] This work was completed as part of a collaborative effort with researchers at Michigan State University and Bowling Green State University.

created by the IPMC sensors, which protrude into the flow. There are four pairs of symmetric slots for pressure sensors and an additional slot at the nose of the body. The sensors are mounted in the forward-most symmetric slots. The extra slots allow flexibility in the sensor configuration and provide the opportunity to expand the sensor array for future experiments. This compact design maintains the smooth surface of the foil while providing enough clamping force to hold all the sensors [1].

Eight IPMC sensors are placed uniformly around the front and sides of the prototype, subject to manufacturing design constraints. The sensor length direction is normal to the foil surface and each sensor is mounted such that it responds to the two-dimensional flow tangential to the foil surface at the mount point. Signals from each sensor are measured, processed, and assimilated into the recursive Bayesian filter by incorporating Matlab functionality within a LabVIEW software interface [8]. The vehicle's orientation and cross-stream position are controlled using an overhead gantry system [1].

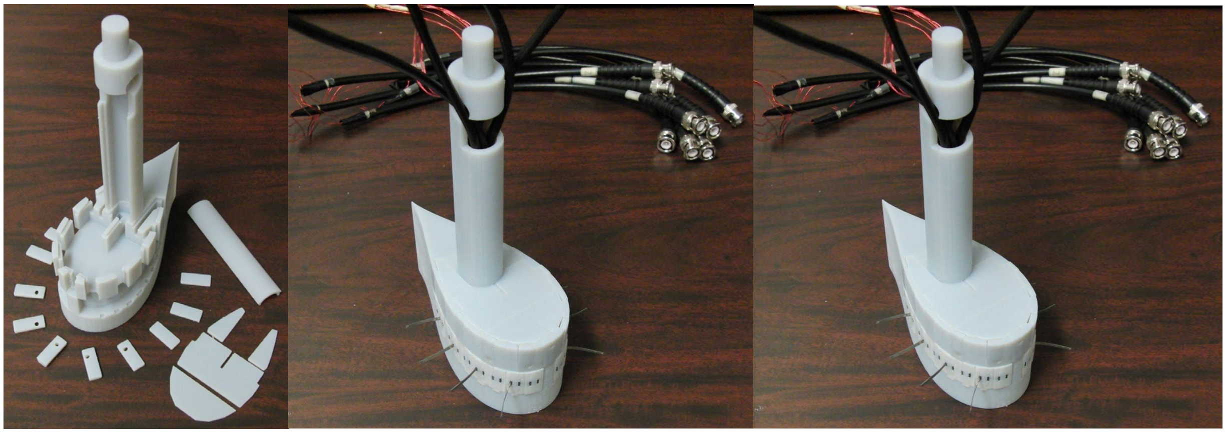

Figure 2: The modular design of robotic foil can incorporate up to twenty IPMC sensors and nine pressure sensors. Current work uses an array of eight IPMC sensors installed below an array of four pressure sensors. Wires are routed inside the body to maintain the streamlined foil shape of the prototype and limit un-modeled viscous effects [1].

We implemented a recursive Bayesian filter to estimate the cross-stream position and diameter of an upstream obstacle relative to the foil. The estimated cross-stream position is used to steer the vehicle behind the obstacle [1]. Figure 3 illustrates experimental results of the closed-loop obstacle position estimation and control algorithm for station-holding. An obstacle with diameter 5.08 cm was centered 5.08 cm upstream of the foil. The left plot in Figure 3 shows the marginal probability density of the estimated cross-stream position. The solid white line corresponds to the actual cross-stream position, whereas the dashed white and magenta lines correspond to the desired and estimated cross-stream positions, respectively. The initial cross-stream position was -5.5 cm. The right plot in Figure 3 illustrates the absolute error between the actual and estimated cross-stream position (solid black) versus time as well as the absolute error between the desired cross-stream position and the estimated (dashed red) and actual (dashed blue) cross-stream positions [1]. Note that despite the estimation error, the feedback control algorithm steers the foil to within 1 cm position error, as shown by the dashed blue line in the right plot.

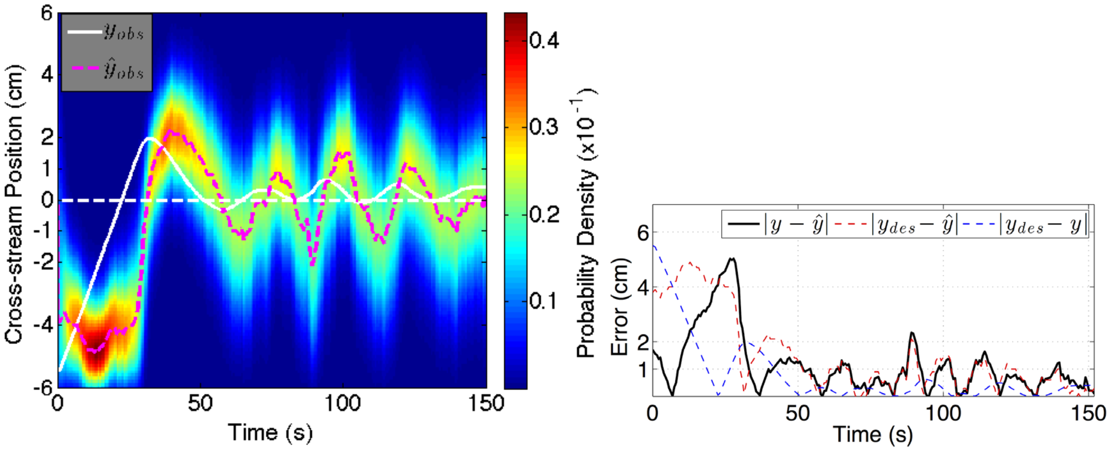

Figure 3: Experimental implementation of station-holding estimation and control. The marginal probability density of (left) cross-stream position plotted versus time with actual (solid white) and estimated (dashed magenta) positions. The dashed white line indicates station-holding corresponding to when the foil lies directly behind the obstacle. (right) Absolute error between estimated, actual, and desired cross-stream positions [1].

Significance and impact

Drawing motivation from the fish lateral line, the research produced under this fellowship proposed new sensing and control strategies that emulate how fish sense and act within their environment. This project successfully demonstrated implementation of a multi-modal, bio-inspired sensing system capable of estimating the position of an obstacle relative to an underwater vehicle. Using the estimated obstacle position, we designed a feedback control algorithm that steered the vehicle to a desired position relative to the obstacle.

Future implications

While this work produced strides forward in the field of bio-inspired sensing and control, it is but a small step down one of many future research avenues. One area of further study is to better understand the robustness characteristics of the control algorithm to estimation error. Additionally, one could adapt the experimental procedure and sensor configuration in order to detect the presence of vortices shed from an upstream obstacle at low Reynolds numbers. Performance of the estimation algorithm in this work could be improved using high-fidelity flowfield and vehicle models, including models with coupled kinematics of the vehicle's angle of attack and cross-stream position.

Bio-inspired sensing strategies like those proposed in this project may one day allow underwater vehicles to operate autonomously in dark, murky, and cluttered environments where traditional sensing modalities are hindered. The ability to operate in these environments can be beneficial for underwater mine detection, inspection of bridge foundations, or exploration of dangerous environments such as nuclear reactors.

2. Bibliography and anticipated publications

Publications anticipated to acknowledge Link Foundation support

[1] L. DeVries, F. D. Lagor, H. Lei, and D. A. Paley. Distributed Flow Estimation and Closed-loop Control of an Underwater Vehicle with a Multi-modal Artificial Lateral Line. Accepted for publication in *Bioinspiration and Biomimetics*, special issue on "Hybrid and multi-modal locomotion".

[2] L. DeVries. Observability-based Sampling and Estimation of Flowfields Using Multi-Sensor Systems. PhD dissertation, University of Maryland, July 2014.

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[7] Z. Ren and K. Mohseni. A model of the lateral line of fish for vortex sensing. Bioinspiration & Biomimetics, 7(3), 2012.

[8] F. D. Lagor, L. DeVries, K. Waychoff and D. A. Paley. Bio-inspired flow sensing and control for autonomous underwater navigation using distributed pressure measurements. In Proc. 18th Int. Symp. Unmanned Untethered Submersible Tech., Portsmouth, New Hampshire, August 2013.

3. Statement of how discretionary funds were spent

Funds from the Link Foundation Fellowship were used solely to offset stipend expenses as a graduate research assistant in the Department of Aerospace Engineering at the University of Maryland, College Park.

4. How did the fellowship make a difference?

The research produced during my time funded under the Link Foundation Fellowship significantly impacted my academic and professional development. Our experimental results validated our prior theoretical conclusions in bio-inspired sensing for autonomous control of an underwater vehicle. As a result, my Ph.D. dissertation contained an expansive experimental component to complement prior theoretical analysis, making the overall contribution vastly more significant. The research also generated new ideas to pursue further in my career in academia. In addition, results achieved during the fellowship garnered local media coverage, disseminating the work to a broad audience.