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DEVELOPMENT OF A PUMP-DRIVEN VERTICAL PROFILER FOR AN
AUTONOMOUS SURFACE VEHICLE

BY
SCOTT HARA

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
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MASTER OF SCIENCE THESIS
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ABSTRACT

A modified SCOUT autonomous kayak, owned by the Roman Lab, performs geo-referenced depth profiles at pre-defined spatial locations. The vehicle uses a single azimuth thruster to approach a goal location, and holds station while a depth profile occurs. Using an autonomous surface vehicle (ASV) to deploy a vertical profiler enables precise but adaptive sampling in typically under-sampled environments. The profiler lowers tubing into the water column with a winch, and discrete fluid samples are taken using a peristaltic pump. A conductivity, temperature, and depth (CTD) probe relates the sample depth to sensor measurements by matching their timestamps. Water quality optical sensors, housed in the vehicle hull, are plumbed in-line with the pump for continuous measurement of pumped water properties. The profiler is designed, constructed, and tested to identify relevant system characteristics, such as flush time.

The system flush time is predicted based on the total profiler volume, and maximum pump flow rate. During flushing, a step response is induced in sensor measurements due to the transition between two discrete samples. Step response testing validates the predicted flush time such that a complete system flush occurs during pump operation. Closed loop tests indicate that the optical sensors are robust to large changes in the fluid sample temperature. The completed profiler is integrated with the SCOUT ASV, and field tested at Upper Pettaquamscutt Basin, North Kingston, Rhode Island.

An initial field trial occurred with concurrent manual vertical profiling done by Dr. Veronica Berounsky. Automated dissolved oxygen measurements are found to correlate with the manual vertical profile. The vehicle's stationkeeping performance is found to be satisfactory by staying within 10 meters of the target point. Subsequent field trials confirmed that automated profiling is consistent,

and repeatable.

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Without the assistance of my advisor, Chris Roman, and funding from EP-SCoR NEWRnet this project would not have come to fruition. Additionally, I would like to thank Veronica Berounsky for her experience with monitoring Upper Pettaquamscutt Basin, and data from a vertical profile taken in December 2017. Finally, I'd like to thank Dave Casagrande and Kris Krasnosky for their technical and moral support throughout the project, along with the rest of the Roman labmates I've shared the space with during my work on this project.

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CHAPTER 1

Introduction

This study presents the development, integration, and testing of a pump driven vertical profiler integrated with an autonomous surface vehicle (ASV). Environmental monitoring of lakes, coastal ponds, and estuaries often calls for vertical profiling at specific locations to monitor temporal trends in water properties. Typical long term monitoring stations include moored platforms and automated winch systems with optical sensors that measure physical and chemical water properties [1]. In recent years, many studies used these platforms for monitoring the effects of short and long term ecosystem trends [2] [3]. Recent studies using remote sensing of surface water properties identified spatial variability that may be overlooked relative to single point measurements [4]. A system capable of autonomous depth profiling enables evaluation of spatial variability in water properties.

1.1 Motivation

Current water quality monitoring techniques establish a record of ecosystem health through periodic grab sampling at static monitoring locations. Conservation groups, such as Watershed Watch, coordinate weekly sampling efforts throughout Rhode Island. Water samples, secchi depth, and temperature readings are taken as part of bi-weekly sampling in lake basins greater than 15 feet deep [5]. The water properties act as trophic state indicators that are linked to the water body health [3, 6]. These measurements form seasonal records for rivers and lakes throughout Rhode Island, and are complemented with periodic vertical profiles.

In lake and reservoir basins, periodic depth profiles can be used to monitor seasonal changes in lake strata. The Rhode Island Department of Environmental Management (RI DEM) defines a “standardized method for performing qualitative

field measurements of a water column profile in lakes, ponds, and reservoirs, using a multi-probe meter.” [5]. A single profile is taken at the deepest region of a lake, and typically requires several hours to complete. In a study performed on a meso-eutrophic lake, Kallio *et al.* indicate that sparse surface measurements can mis-represent basin scale chlorophyll trends [7]. Although moored vertical profilers reduce the expense of short term monitoring, multiple moorings are required to achieve any spatial resolution [3].

Expanding water quality monitoring coverage is typically handled using a small boat, or autonomous surface vehicle (ASV) to deploy a sensing payload. ASV systems generally include rapid measurement systems, like those deployed from small boats by Antilla in 2008, and Crawford in 2015, with flow cells to measure surface properties on a lake [8, 9]. Coupling optical sensor measurements with the vehicle position enables mapping of spatial water quality trends. Other systems, such as the one deployed by Birgand in 2016, increased the spatial coverage of a single sensor using a multi-port valve and peristaltic pump [10]. A key component of all three studies was a flow cell that established a closed volume between a sampled environment and optical sensor. Using a flow cell system also reduces the likelihood of sensor damage they aren’t exposed *in-situ*. Similar systems used an ASV to deploy a water quality monitoring payload to great effect.

In recent years, ASVs have proven to be suitable platforms for deploying monitoring payloads. The Lake Wivenhoe ASV successfully deployed a profiling arm capable of reaching “up to 20m when the vehicle is stationary” [11]. Additional work examined diurnal variation in methane effusion at the Little Nerang Dam reservoir using the Wivenhoe and an *Inference* ASV [12]. The Woods Hole Oceanographic Institute (WHOI) Jettyak deployed a CTD sensor using a small winch and A-frame similar to traditional research vessels [13]. In 2015 the Hy-

dronet ASV was deployed with the sensors necessary to optically and chemically track hydrocarbon trails. Using a custom built CTD rosette it can extract up to 7 samples from the water column during a profile [14]. Water sampling payloads in these vehicles were custom built, and required experimental validation to establish their operating parameters.

1.2 Purpose of Study

This document presents the design for a pump driven vertical profiler that will be used to examine spatial variability of water properties. The primary criteria for the profiler is that sensors are housed in the hull of the vehicle, rather than deployed *in-situ*. Fluid will be extracted from depth using a peristaltic pump, and pumped to a series of optical sensors in a closed system created by flow cells and Tygon rubber tubing. The following list describes the major design goals:

1. A closed system will be established between a point at depth, and the sensors in the vehicle.
2. The effects of system operation on a fluid sample will be characterized to determine if it is representative of the *in-situ* water properties.
3. The vertical profiler will be integrated with an existing SCOUT ASV, and field tested to evaluate its performance.
4. Measurements will be compared with other routine profiles.

Flow cells create an independent, closed volume around each sensor. When the system is flushed the sensors take real time measurements of the water passing through each cell. A conceptual overview of the final system design is presented in Figure 1.

Figure 1: The proposed vertical profiler pumps water from depth to sensors housed in the vehicle hull. Each sensor is encapsulated in a flow cell

Component development occurred between October 2016 and was completed July 2017. Integration of systems with the ASV occurred in parallel with development between March and August 2017. Final iterations of the vertical profiler were completed by August 2018, and ASV upgrades were completed by June 2018 to improve the vehicle’s surveying performance. The completed system was field tested at Upper Pettaquamscutt Basin, North Kingston, Rhode Island, where there are strong water column features, and a history of prior monitoring. Chapter 2 will discuss the vertical profiler design, the proposed method of operation, the optical sensors used, and the basic system characteristics. Chapter 3 discusses the measurement response testing that validates the system’s performance, and its integration with the ASV. Finally, testing results for the profiler and ASV are presented in Chapter 4.

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CHAPTER 2

Design Overview

This chapter presents the design for the pump driven vertical profiler. The system deploys Tygon rubber tubing to depth using a winch and extracts fluid via a peristaltic pump. A conductivity, temperature, and depth (CTD) probe is attached to the deployed tubing for measuring physical *in-situ* water properties (Figure 2).

Figure 2: A conceptual diagram of the vertical profiler integrated with the Roman Lab ASV. The CTD attached at the tubing inlet provides the actual sampling depth during a profile. Fluid extracted by the peristaltic pump is fed to several optical sensors located within the vehicle and then expelled.

Within the vehicle hull optical sensors are plumbed in-line with the peristaltic pump. Flow cells fitted around each sensing head provide a suitable fluid volume for optical measurement of water properties.

During profiling operations each sensor logs continuously so that the complete system response is measured. A prescribed flush time, described in Section 2.3, is used to time the pump operation such that the sensor readings relate to the fluid sampled at depth. Figure 3 summarizes the operation for a profile to several prescribed depths. An estimate of winch payout, described in Section 2.2, is used to control the winch and deploy the sampling tube to the desired depth.

Figure 3: A flow chart representing the automated depth profiling method. Water properties are measured after a set duration of pump operation.

The following sections introduce the components used in the vertical profiler starting with optical sensors and their flow cells in Section 2.1. Physical characteristics of the winch and a procedure used to refine the motor encoder counts to payout conversion are presented in Section 2.2. Experimental determination of the pump flow rate and total system volume are presented in Section 2.3.

2.1 Optical sensor integration

Optical sensors are ubiquitous tools for estimating *in-situ* water properties through various physical proxies. Utilizing a photo diode and detector these sensors emit light into a fluid volume and measure the response. The operating principles for each sensor are unique and affect their sensitivity to a closed volume. Each

sensor is housed in an independent flow cell designed to suit the unique fluid volumes required. The sensors deployed for this study are seen in Figure 4.

Figure 4: Water quality sensors deployed for this study: Ecopuck fluorometer (a), Aanderaa Oxygen Optode 4835 (b), and s::can spectrolyser (c).

The following subsections detail the operating principles of each optical sensor and discuss how their measurements are related to the water properties of interest.

2.1.1 Ecopuck Fluorometer

The fluorometer is a tri-parameter sensor that measures chlorophyll, turbidity, and fluorescent dissolved organic matter (FDOM). It excites the water volume in front of the sensor head with 460 and 690 nm light and measures the return at 695 nm. Chlorophyll fluoresces when excited by blue light and a strong correlation exists between the emission and real chlorophyll concentrations [1]. Sensor

measurements are made in raw sensor “counts” that are mapped to their relevant properties through a linear fit. The following equation describes the calculation applied to all measurements made by the fluorometer.

$$[chl, turb, CDM] = SF \cdot (counts - darkcounts), \quad (1)$$

Where the coefficients SF and $darkcounts$ are unique for each property and are specified by a manufacturer calibration. Validation of the sensor’s response is performed through a combination of dark count tests and testing with turbidity standard. Dark counts are determined by placing tape over the sensor head so that no light is able to reach the detector. Comparison of the reported dark counts with the calibration dark counts indicates that no linear offset exists at the zero point of the sensor.

2.1.2 Aanderaa Oxygen Optode

An Aanderaa Oxygen Optode 4835 is deployed to measure dissolved oxygen and air saturation. Measurements are conducted using a process called Dynamic Luminescent Quenching. The sensor excites an oxygen permeable foil with blue light which is quenched by the release of oxygen from the foil. Figure 5 represents the physical relationship between the light emission and oxygen concentration in its sensing foil.

Figure 5: Manufacturer’s Representation of Dynamic Luminescent Quenching, Optode Principles of Operation [2]

Using the Stern-Volmer equation the oxygen optode relates the delay in the luminescent response to an oxygen concentration [2]. Measurements are sensitive to changes in salinity and temperature, but for this study only temperature compensation is applied to measurements taken. A multi-point factory calibration provides the necessary coefficients for relating the sensor readings to oxygen concentration. Basic functionality tests of the optode can be made by placing the sensor in an open container and blowing bubbles into the water. The sensor responds by showing an increase in the O₂ concentration to the point of air saturation, verifying its operation.

2.1.3 scan spectrolyser spectrometer

An scan spectrolyser is a relatively new sensor typically used in measuring the water properties of effluent discharge from wastewater facilities. It estimates nitrate, turbidity, fluorescent dissolved organic matter (FDOM), and total organic carbon (TOC) quantities in the water volume seen in Figure 6 using a 15mm

sensing channel path.

Figure 6: s::can spectrometer sensing channel. A xenon light emits a pulse of UV-VIS light into the sensing channel. A proprietary calibration method enables measurement of *in-situ* nitrate (NO_3). [3]

The sensor is calibrated using a partial least squares (PLS) method with training data gathered from five wastewater treatment facilities. By incorporating the entire spectral response in the calibration Langergraber *et al.* identify the capacity for *in-situ* nitrate detection in concentrations of 0-5 mg/L [3]. A second, single point calibration is applied to the sensor prior to field testing using a distilled water bath. Two constraints reduced the effectiveness of this sensor during deployments. The measurement requires one minute to process data, and typical aquatic nitrate concentrations in coastal ponds are significantly lower than the ones identified in the training data. As a result this sensor was deployed in preliminary field trials but removed from the system during the remaining tests.

2.1.4 Flow Cell Design

Flow cells are constructed to encapsulate each sensor and place a suitable fluid volume in front of the sensing head for normal operation. Inside of a closed volume the cell walls can reflect incident light back towards the sensor and potentially introduce measurement bias due to the cell itself. The s::can and oxygen optode used in this study are not influenced by reflection but still require a minimum head space to operate nominally. Experimental determination of this effect was

performed through proximity testing of each sensor. A matte black surface was placed on the bottom of a bucket to represent a flat cell wall. Each sensor was placed facing the surface and measurements were made while lowering the sensor towards the surface. Homogeneity of fluid in the bucket implies that differences in the sensor response during lowering are caused by reflection off the cell wall. As a result the final Ecopuck housing, seen in Figure 7, had a greater head space volume than the oxygen optode and scan.

Figure 7: Section diagram of the Ecopuck fluorometer flow cell. The sensing volume is considerably larger relative to the other cells due to the brightness and orientation of the sensor head.

Each flow cell is fabricated using 3D printed ABS with a coat of epoxy on the inside for waterproofing. Hose barbs epoxied into the inlet and outlet provide airtight connection points for tubing, and are oriented so that bubbles cannot get trapped within a cell. An o-ring between the cell wall and sensor body closes the volume. This establishes the sensor payload deployed in the vertical profiler.

2.2 Winch

A small level-wind winch is outfitted with a high torque gearbox and Animatics Smartmotor, model SM23165MT, to control the profiler depth. Typical motor operation draws 30W with transients up to 50W depending on winch tension. The

winch is spooled with 50 feet of Tygon tubing and a YSI Castaway CTD is attached at the deployed end with a cable grip. The drum is geared to the level wind to manage the tubing during winding. Plumbing within the winch drum connects the spooled tubing to the pump using a fluid slip ring. An image of the completed assembly with tubing un-spooled from the drum is seen below:

Figure 8: Winch with 5/16" Tygon rubber tubing spooled on the bench. High torque gearbox and Smartmotor are seen below the fluid slip ring.

The motor uses an internal encoder to measure the shaft position during operation. A relationship between commanded motor shaft positions and an actual payout length is described by the winch and gearbox characteristics as

$$payout = encoder\ counts * \frac{drum\ circumference}{motor\ counts\ per\ revolution * gearbox\ reduction\ ratio}. \quad (2)$$

The drum and wire guide were geared together such that the tubing wind was less consistent than Equation 2 implies. Field trials were performed to evaluate the tubing wind consistency and refine the conversion between encoder counts and payout length. At Upper Pettaquamscutt Basin the winch was driven to a depth target of 8 meters with five unwind-wind cycles to generate a calibration between encoder count and CTD depth. During field trials the original coefficient

is found to underestimate the quantity of deployed tubing due to the constant drum circumference assumed. Figure 9 displays this under-estimation as well as the linearity observed during multiple payout cycles.

Figure 9: A graph comparing the original encoder-payout estimate to the one identified during field trials. No hysteresis is observed and the payout response is linear.

The final coefficient is used for driving the winch to a set depth, and the average speed of the winch is 10 cm/s. Further linear offsets were also used to zero the payout amount once the profiler is mounted in the ASV. This accounts for the distance between the winch and water's surface.

2.2.1 YSI Castaway CTD

Measurement of *in-situ* conductivity, temperature, and depth is handled by a YSI Castaway CTD. The device records measurements to internal memory and is timestamped relative to a GPS-synced clock. During a survey the Castaway is attached to the tubing using a cable grip and configured to log continuously. Survey data are retrieved from the device after a deployment and matched to logs collected by the vehicle based on matching timestamps. CTD data provide a

reference for the tubing depth and *in-situ* physical properties of the sampled fluid for validation purposes.

2.3 Peristaltic Pump

A Cole Parmer Masterflex peristaltic pump is used to draw water from depth up the sampler tube. Peristaltic pumps are typically used when a closed sample path is necessary to measure fluid properties. These pumps minimize pump-fluid interactions by squeezing tubing between several rollers to generate pulsed fluid flow and do not entrain air. Two diameter pump heads were selected for testing. The LS-24 and LS-36 pump heads accept 1/4" and 5/16" diameter tubing respectively. A Pololu 24V motor controller drives the pump, drawing up to 60W at full speed.

The flow rate was determined using repeated 30 second trials of pump operation. Each pump head was loaded with a one meter length of tubing, and operated for ten minutes to ensure that the tubing was broken in. Next, the pump was run for four 30 second intervals. For each test a kitchen scale was used to measure the pumped fluid mass and establish baseline variability in the flow rate. As expected the larger pump head displaces 35% more fluid compared to the smaller one with a subsequently higher variance across all trials. The observed deviation is around 2.5% of the total volume pumped.

Pump Head	LS-36	LS-24
Pump Time (sec.)	30	30
Mean Fluid Pumped (mL)	896	661
3x Standard Deviation (mL)	21	15

Table 1: Flow rate comparison between the LS-24 and LS-36 pump heads. Variance in the displaced fluid is between 2.2% and 2.5% relative to the mean.

Adding additional tubing induces pressure losses dependent on the length and tube fittings. Flow restrictions were characterized for individual plumbing

components to identify major sources of head loss and minimize them if possible. The system plumbing was connected to the pump relative to the numbering in Figure 10. Table 2 describes the system configurations tested with the LS-36 pump head.

Figure 10: A connection diagram with system configurations marked relative to Table 2.

Components	Displacement (mL)	Loss (Percent)	Configuration
5/16" to 1/4" fitting, inlet and outlet	846	-5.6%	1
5/16" fitting inlet, 5/16" to 1/4" fitting outlet	857	-4.4%	2
1/4" tubing, 50 feet	522	-41.5%	3
5/16" tubing, 50 feet	784	-12.5%	4
Winch with fluid slip ring and internal fittings	887	-1%	5
Winch, and 5/16" tubing	756	-15.6%	6
Winch, 5/16" tubing, and one flow cell	681	-24%	7
Winch, 5/16" tubing, and all flow cells	681	-24%	8

Table 2: A list of system configurations evaluated to identify the sources of flow rate loss in the profiler.

Flow rate tests with these setups follow a similar procedure to the one described for identifying the nominal flow rate. A given system configuration from Table 2 is connected to the pump and filled with water. Pump operation occurs for 30 seconds and again discharged fluid is collected and weighed. Three tests were conducted for each system configuration and their average flow rate was compared to a nominal flow rate described in Table 1. A clear advantage is seen between 1/4" and 5/16" tubing. The final plumbing configuration was selected using 5/16" tubing for all components except the flow cells due to their construction. The final flow rate was used to predict a minimum flush time for the profiler. Table 3 identifies the volume associated with the individual parts of the flow system.

Component	Tubing	Flow Cells	Winch	Pump	Interconnects	Total
Volume (mL)	820	220	20	20	80	1100

Table 3: A table outlining the various fluid volumes associated with the major plumbing components.

Flow cell internal volume was identified by filling an empty cell with water and draining it into a container for weighing. The tubing, pump, winch, and interconnection volumes were determined based on their inner diameter and total length. Combining the total volume identified here and the nominal reduced flow rate from Table 2 yields a minimum estimated flush time of 48 seconds.

2.4 Final Profiler Characteristics

The final profiler characteristics are listed in Table 4. A consequence of the single inlet system design is that a new sample flushes the previous one out. Doubling the minimum estimated flush time ensures that no water from a prior sample resides in the flow cells. Tests conducted in Chapter 3 were completed to determine if the system completely flushes within the predicted time.

Description	Value	Parameter
Total system volume	1100 mL	Volume
Max flow rate	23 mL/s	Flow Rate
Minimum flush time, min	45 sec	T_{flush}
Predicted flush time	90 sec	T_{flush} , predicted
Measurement after flush	30 sec	$T_{measure}$
Average winch payout speed	10 cm/s	S_{winch}
Sensor power	12W	$P_{sensors}$
Pump power, full speed	60W	P_{pump}
Average winch power	30W	P_{winch}

Table 4: Final system characteristics to automate the profiling method described in Figure 3

The time and energy required for a profile are described by the following equations.

$$T_{profile} = (T_{flush} + T_{measure}) \cdot N + (2 \cdot D_{max}/S_{winch}) \quad (3)$$

$$E_{profile} = (P_{pump} \cdot T_{flush}) \cdot N + (2 \cdot D_{max}/S_{winch})(P_{winch}) + (T_{profile} \cdot P_{sensors}) \quad (4)$$

Where N is the number of samples and D_{max} is the maximum depth. Pump operation is the limiting factor during a profile. For example, taking ten measurements with a D_{max} of 15 meters requires 0.25 Wh for winch operation, 30 Wh for pumping, and 9 Wh to operate the sensor. The time required for ten measurements is approximately 30 minutes, 20 minutes for sampling and 10 for winch operation. This system power requirement was accounted for by upgrading the vehicle power source. Four lithium iron phosphate ($LiFePO_4$) batteries increased the available power from 1,260 Wh to 1,680 Wh. The additional power provides is sufficient for between 60 and 100 measurements during a survey.

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CHAPTER 3

Profiler Evaluation and Integration

Sensor measurements will exhibit a delayed step response when a prior sample is flushed from the system by a subsequent one. The completed system, seen in Figure 11, underwent an evaluation to verify the predicted flushing characteristics defined in Chapter 2.

Figure 11: A bench setup of the completed sampler layout. Fluid travels along the path marked by the blue arrow and passes through the flow cells before draining to a waste outlet.

Fluid sampled by the pump takes 30 seconds to travel through the tubing to the cells. The step response induced by flushing is dependent on the flow cell volume and sensor response time. To measure this response fluids with distinct levels of turbidity and oxygen concentration were run through the system. Table 5 defines the expected sensor measurements for three distinct fluids.

Fluid	O_2	Turbidity
Distilled Water	$\geq 200 \mu\text{mol/L}$	$\leq 5 \text{ NTU}$
Turbidity Standard	N/A	$\geq 20 \text{ NTU}$
Anoxic Water	$0 \mu\text{mol/L}$	N/A

Table 5: Fluid standards used to induce a large amplitude step response at the fluid interface change during pump operation.

Sensors were connected to the profiler and flushed, alternating between the standard of interest and distilled water. The predicted flush and measurement periods were used to represent the system operation in the field. Waste water from the fluorometer trials was collected and re-run through the system to test the sensor response at varying turbidity concentrations. The following subsections present the results from these trials and additional sensor-specific tests to further characterize the system operation.

3.1 Ecopuck turbidity response

Figure 12 shows that a complete measurement response is observed during the predicted 45 second flush time.

Figure 12: Turbidity measurement step responses for three standard concentrations.

The transients seen in Figure 12a at 38 seconds and Figure 12b, were caused by air bubbles entrained in the fluid flow when switching fluid volumes. No hysteresis was observed in either set of step responses, and the response time is consistent across varying concentrations of turbidity standard. Since the fluorometer responds quickly the step response is primarily associated with its cell flushing.

An additional experiment passed a small “spike” of concentrated turbidity standard through the system between distilled water flushes. The observed tur-

bidity measurements seen in Figure 13 verify the response time identified previously and the extent of mixing that occurs. These tests imply that only measurements taken after pumping for 90 seconds are representative of the fluid sampled at depth.

Figure 13: Ecopuck measurement response to a 100 mL spike of turbidity standard introduced to the system between distilled water flushes. An asymmetric response is observed because mixing occurs in the chamber during flushing.

3.2 Optode oxygen response

Step response tests using the oxygen optode were conducted with anoxic standard and distilled water. In Figure 14 the complete response of the sensor and chamber occurs within the predicted flushing interval. This is consistent with the sensor specifications, of a 63% response after 25 seconds [1]. The ramp up observed in Figure 14a was caused by air introduced at the tubing when water volumes were switched.

(a) Oxygen optode step response, high concentration to low concentration. (b) Oxygen optode step response, low concentration to high concentration.

Figure 14: The oxygen optode step responses indicate a delayed response when pumping anoxic fluid. A complete sensor response is observed within the predicted flush time.

During pump operation the fluid temperature changes as it travels through the system from depth and to the sensor in the kayak, which may induce measurement error. This effect was characterized with a closed loop “radiator” test. A length of tubing was filled and connected to the pump and flow cells to create the closed loop. The tubing was submerged in a bucket of warm water to heat the fluid inside. Water was flushed past the optode until an increase in temperature was measured. Pumping was stopped and the tubing loop was placed in a bucket of ice water. Once chilled pumping occurred again until a large temperature change was observed by the optode thermistor. In this experiment a temperature change of 7 degrees C was forced to represent a more extreme range than expected in the field. During field operation temperature changes are typically small, between 0.5-1.5 deg C, and the residence time of a sample is 2 minutes.

Figure 15: Closed loop temperature response of the oxygen optode. The temperature deviation during the closed loop trial was 7 degrees C. Variability in the subsequent measurements are well below the 5% accuracy of the optode thermistor. Therefore temperature changes to the fluid do not affect the sensor measurements.

A negative trend occurs because oxygen solubility is dependent on fluid temperature. Over a ten minute period, the temperature measurement never equalized, indicating that small systemic bias exists due to pumping water into a warmer environment. Although the change was negligible in lab conditions large temperature differences between the surface and depth will affect the oxygen measurements slightly.

3.3 Vehicle overview and profiler integration

The vertical profiler was integrated into a SCOUT autonomous kayak (in Figure 16).

Figure 16: Scout ASV with sheave and winch mounted.

The SCOUT autonomous kayak uses a single azimuth thruster to drive survey patterns defined in a prescribed mission plan. The water quality sensors and pump were housed within the hull, while the winch is mounted on top. Battery power for the vehicle was provided at 12 and 24V. An overall schematic for the vehicle is seen in Figure 17.

Figure 17: A high level diagram of power and communications between kayak devices, and the on-board computer.

All sensor communications on-board are handled digitally via RS232 or RS485

to USB converters. Software drivers read and publish data from each message pass over UDP using Lightweight Communications and Marshalling (LCM) [2]. These data are logged continuously during a survey. In post-processing message timestamps for profiler state and Castaway CTD are matched to generate a representative depth profile.

Three primary software daemons are seen in Figure 18. Sensor drivers handle communication with the vehicle computer through a single point of contact. A profiling daemon handles pump and winch commands independent of the mission executor. The mission executor handles the overall operation of the vehicle and interacts with the controller which commands the thruster and rudder.

Figure 18: A high level software diagram controlling the vehicle.

Line following and hold station behaviors permit the vehicle to approach a target point, and stay within 10 meters of it until a profile is complete. Once on station, a profile command sent to the profiling daemon indicates depth targets, flush time, and measurement time. The mission executor maintains station-keeping until the profile is complete, or aborts due to shallow conditions. An example of a

profiling mission can be seen in Figure 19.

```

GLOBAL
    mis_timeout 1:50:00
    min_depth .8
    enable_battery_abort 0
    battery_cutoff 10
    enable_aimar_abort .8
    enable_ysi_abort 0
    enable_shore_hb_abort 0
    origin LAT 41.51498 LON -71.44506
    home X 0 Y 0
    speed 1.25
    bounding_box /kayak/MISSIONS/20170927_transect.kml
    offset 5
    boundary_buffer 5
ENDGLOBAL

SAMPLE_POINT
    speed 0.5
    leg_timeout 45:00
    position X -50 Y 0
    depths [1,2,3,4,5,5.5]
    flush_time 90 # sec.
    measure_time 30 # sec.
ENDSAMPLE_POINT

HOME
    leg_timeout 30:00
    speed 1.5
ENDHOME

```

Figure 19: Example mission file sent to the vehicle prior to a survey. Global parameters define critical timeouts and the local reference frame. Positions during a survey are then referenced to that origin. An array of depths, a flush time, and measurement time specify how an automated profile will be performed at the target location.

Integration of the profiler required a series of upgrades to the platform, according to the following list.

1. Four lithium iron phosphate batteries increased the vehicle power capacity available for payload operation.
2. An upgraded cockpit cover provided hard points for securing the winch on top of the kayak.
3. A sheave mount was constructed to pass the tubing to a through hull fitting.
4. An RTK GPS reduced vehicle position uncertainty from roughly 10 m to ≤ 10 cm.
5. A powered USB hub supported communications between the profiler components and main vehicle computer.

6. A limit switch mounted in the sheave established a set point for resetting the winch payout after a profile.

Field tests evaluated the overall system performance, and provided a validation case for the representativeness of measurements taken.

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CHAPTER 4

Field Testing

The ASV and profiler were field tested at Upper Pettaquamscutt Basin, North Kingston, Rhode Island. The basin maintains stratified layers that act as signals indicating new water masses in the profiler. Datasets from two deployments in December 2017 and June 2018 are presented. Profiles from December 2017 were taken concurrently with Dr. Veronica Berounsky, who performed a manual vertical profile with a YSI Exo Sonde. Additional profiling in June 2018 increased the spatial range of vertical profiles, and doubled the number of points per profile. Background information on the site is presented in Section 4.1, and field trial results are discussed in Section 4.2.

4.1 Site Overview

A study published by RI DEM describes the Narrow River Estuary as a composite of a tidal inlet and back bay, an estuary, and two fjord-like ponds [1]. Upper Pettaquamscutt Basin, seen in Figure 20, stays heavily stratified year round due to tidal and riverine forcing. It is historically well monitored with studies identifying anoxic conditions at the bottom, and unique concentrations of biogenic hydrogen sulfide [2]. Subsequent profiling identified fine scale plankton layers that are on the order of centimeters thick [3].

Figure 20: Narrow River Estuary, South Kingstown, Rhode Island. The colored regions indicate the transect taken by the ASV during field testing on December 7th, 2017.

Each deployment followed a prescribed mission similar to the outline from Figure 19. All deployments were referenced to the same local origin for consistency. In December, four depths (2, 4, 6, and 8 meters) were selected for profiling. Two profiles were conducted at the same spatial location as a control, and two additional profiles were executed 50 and 100 meters west of the starting location. Dr. Berounsky performed a manual depth profile, using a YSI multiparameter sonde, 50 meters west of the survey transect. A YSI sonde measures dissolved oxygen and chlorophyll fluorescence, and is specified by RI DEM as the required sensor for vertical profiling [4] [5].

The vehicle depth profiles were extracted in post processing by referencing the Castaway CTD data to mission logs relative to their timestamp. Each sample taken during a profile was assigned a unique identifier based on the profiling daemon assignments for sample, and depth index. Sensor readings taken during $T_{measure}$

were averaged, and referenced to their extraction depth. A 45 second offset was applied to the Castaway measurement of tubing depth, reflecting the system flush time. As mentioned earlier in Subsection 2.1.2 dissolved oxygen concentration data was not salinity corrected. A factory calibration was applied to raw fluorometer data to estimate chlorophyll density.

4.2 Field trial results

The dissolved oxygen profiles, seen in Figure 21a, indicate correlation between *in-situ* conditions, and sensor measurements taken by the profiler. Variation in the tubing depth during sampling was negligible relative to the CTD pressure measurement accuracy. The largest variance in dissolved oxygen measurements was observed directly in the oxycline. Vehicle motion during each profile was within a 10 meter radius circle of the goal, seen in Figure 21b.

(a) O_2 concentration depth profiles. (b) Distance from point for each profile.

Figure 21: December 2017 field testing results. The ASV held station within a 10 meter radius of the goal point, and took fluid samples representative of the expected layers within the basin.

This field trial validated the system performance relative to an established depth profiling method. Additional profiles were conducted in June 2018 that expanded the number of profiling locations and depths sampled by the ASV. Vehicle stationkeeping performance, seen in Figure 22, was consistent with the December

trials.

Figure 22: Profile locations for each profile. The ASV performance was consistent with prior trials.

The profiles taken in June are typical of seasonal water column trends. Chlorophyll and dissolved oxygen maxima reside within the steepest gradient of the pycnocline, seen in Figure 23.

(a) Oxygen optode depth profiles indicate that the O_2 maximum is oversaturated. (b) Chlorophyll density depth profiles indicate high concentrations of biomass populating the oxycline.

Figure 23: June 2018 field trial depth profiles of dissolved oxygen and approximate chlorophyll density.

4.3 Future work and conclusion

For this study, a pump-driven water sampler was integrated with an ASV, and field tested. Flow cells encapsulated optical sensors which were plumbed in-

line with a peristaltic pump. A system flush time was predicted by characterizing the pump flow rate, and evaluating the sensor measurement response confirmed that a full flush occurred after the predicted interval. The profiler was integrated with an existing ASV, and is capable of performing between 80 and 100 discrete measurements during a profile. Finally, field trials at Upper Pettaquamscutt Basin validated that measurements taken by the profiler are representative of the *in-situ* fluid properties.

Field trials validated the predicted system performance, and further work will explore the impact of profiling on local fluid interfaces. Tubing movement through the water column causes stirring, and can potentially disturb fine chlorophyll layers. Additionally, the physical processes driving local fluid properties are time varying, and may change if a region is profiled again.

Chlorophyll measurements made by the fluorometer are not physically grounded, and require a correction based on a physical determination of chlorophyll concentration. The correlation between *in-situ* and sampler conditions indicate that sampled fluid may be stored for future processing. Due to space constraints within the ASV sampling and sensor measurements are currently mutually exclusive. Moving forward, further vehicle upgrades will permit simultaneous measurement and sampling operations.

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