DESIGN AND SYSTEM IDENTIFICATION OF A LOW-COST USV FOR COASTAL OBSERVATION

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DESIGN AND SYSTEM IDENTIFICATION
OF A LOW-COST USV
FOR COASTAL OBSERVATION

BY
ROY GILBOA

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE
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ABSTRACT

Monitoring areas near shore is often performed using unmanned surface vehicles but can be hampered by high cost and complexity. Existing vehicles can be expensive and difficult to operate. Recent development of consumer- and hobbyist-oriented marine hardware and control software have enabled the creation of vehicles that solve these problems. In this project, a low-cost, SUP-based USV was constructed and proved itself to be portable and capable of performing surveys at several sites in Rhode Island, with an approximate cost and vehicle mass of $3,500 and 20 kilograms respectively. It was also evaluated to determine its hydrodynamic properties and its response to wind disturbances in yaw. Analysis of maneuvering trials performed with the vehicle generated accurate hydrodynamic coefficients and preliminary characterization of the relationship between vehicle yaw and wind conditions.
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The Indian Lake association, The Nature Conservancy, the City of Newport, and
the City of East Providence for allowing the use of their property for vehicle
testing.

I dedicate this thesis to my family and friends, without whom I would never have started
this project, and to my Rhode Island family, Emily, Maria, and Paige, without whom I
would never have finished it.
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INTRODUCTION

Coastal areas are threatened by rising sea level and pollution. Erosion and flooding induced by sea level rise jeopardize the integrity of coastal infrastructure, such as transportation and water supplies [1]. Flooding events made more extreme due to higher sea levels can cause the release of pollutants from wastewater treatment plants and cut off low-lying communities whose connections to inland areas are near bodies of water [1]. These issues are of particular concern in Rhode Island, where much of the state’s population and developed areas are located near the coast [1]. More frequent tracking of changes in these areas may help guide decisions on policies to make them more resilient through improved modeling of flooding, erosion, and pollution spread.

Above the water’s surface, such monitoring can be carried out using readily available unmanned aerial vehicles (UAVs; drones) equipped with cameras or Global Navigation Satellite System (GNSS) surveying equipment, but this leaves the underwater topography unknown [2]. Bathymetry surveys with unmanned surface vehicles (USVs) can collect this data, but many commercially available options are expensive and unwieldy [3]. As a result, they cannot be deployed due to lack of resources in some situations where they could otherwise provide valuable insight. By constructing such a survey vehicle with open-source or off-the-shelf components, the cost of a viable system could be reduced. Identifying an accurate dynamic model of the vehicle would enable the creation of a model-based controller, reducing equipment complexity and tuning requirements, thereby lowering the barrier to entry for untrained operators. Overall, a low-cost, portable, easy-to-operate USV could increase the number of scenarios where a robotic survey is feasible with given resources, increasing the amount of data collected in coastal areas.
The selection of a hull for such a vehicle is important, given that it significantly affects the maneuvering characteristics, portability, and allowable payload. Several types of commercial watersports equipment may be suitable as low-cost USV hulls [4]. Some have been used as platforms for coastal monitoring but have not been extensively studied to determine their hydrodynamic properties [5]. Inflatable standup paddleboards (SUPs) are of particular interest given their ability to be deflated for transportation. Using a SUP as the hull of the vehicle would demonstrate its suitability or lack thereof for this purpose.

In this study, a SUP-based USV was constructed and proved itself capable of performing useful surveys at several sites in Rhode Island. It was also evaluated to determine its hydrodynamic properties and its response to wind disturbances in yaw. Further work is needed to combine these properties into a unified model suitable for the longer-term goals of closed-loop controller simulation and model-based control. Improvements could also be made to simplify the vehicle’s mechanical design, as well as extend the capabilities of its firmware and installed sensors.
BACKGROUND

The development of the Geophysical Feature Finder (GeoFF) vehicle used in this research effort was enabled by the confluence of several technological innovations that have occurred since the early 2000s. This concept relied on the existence of consumer-grade components that could be combined to obtain capabilities similar to that of a commercial vehicle.

First among these advances is the development of inflatable standup paddleboards, which were first marketed in 2007. Previous boards were rigid and bulky, with dimensions similar to that of a surfboard, and could not be collapsed or folded for transportation [6]. Since that time, inflatable SUPs have become extremely common, with Google searches for inflatable paddleboards in the United States increasing by a factor of more than ten after their market introduction [7]. This popularity likely contributed to the wide variety of paddleboards available for use in this vehicle.

Many of the electronic components used on the vehicle were also not available until a few years ago. The autopilot and associated open-source ArduPilot firmware are both recently developed components that form the core of the vehicle. The ArduPilot code repository was first created in 2009, with the L1 navigation controller originally used for fixed-wing aircraft, and later adapted for boats, released in 2013. Rover firmware implementing skid steering, analogous to the differential steering used on GeoFF, was first available in 2017. The first firmware release to include support for boats was published in 2018, with further refinements added since that time [8]. The Cube Orange autopilot running the ArduPilot Rover firmware used in this vehicle traces its origin to a reference design first manufactured in 2014 [9]. In addition, Ardusimple, RTK GNSS receiver manufacturer, was only founded in 2018, with the simpleRTKV3 receiver
released sometime after that [10]. The introduction of these components represents a significant capability marketed to lay users, with prices to match, that was previously not available.

The vehicle’s mechanical components and carbon fiber (CF) frame are also new developments. The carbon fiber frame would have been complex to implement without the DragonPlate modular tube connector system. This system eliminated the manual layup and curing that would have otherwise been necessary to fabricate a carbon fiber frame, while also obviating the need for drilling holes that would have weakened the CF tubes. This system was patented in 2018, making it a relatively new product at the time of this vehicle’s conception [11]. Blue Robotics, the manufacturer of the thrusters, sonar, and motor controllers installed on this vehicle, was founded in 2014 [12], with the T200 thrusters first released the next year [13]. While it may have been possible to produce or acquire similar components independently, the existence of commercial options vastly simplified vehicle fabrication.

The key components of GeoFF have for the most part existed for less than a decade. They are mainly marketed towards consumers, hobbyists, or other users working with limited external support and funding. For this reason, they lend themselves to use in a low-cost, accessible vehicle design.

Other vehicles with similar design goals have previously been marketed or studied. However, they generally do not combine the shallow water bathymetry capability with low hardware cost, ease of fabrication, high payload capacity, flexibility, and portability, instead compromising on one or more of these features. Seafloor Systems is a manufacturer of such vehicles founded in 1999 and based in Shingle Springs,
California [14]. Their lowest-end vehicle, the HyDrone, uses a catamaran design with two HDPE hulls, two Blue Robotics thrusters, a single beam echosounder, and sufficient endurance to perform surveys with a track length of 16 kilometers. While it combines a number of useful features, its payload mass capacity is only one fifth that of a small inflatable SUP and therefore cannot be expanded significantly [15]. Its twin polymer hulls are also not manufacturable without substantial tooling and supporting infrastructure in the form of molds. Another comparable vehicle is the Calypso USV made by dotOcean in Belgium [16]. This USV is based on a custom inflatable platform, is transportable by a single person, and supports single-beam bathymetry surveys with track lengths of 6 kilometers [17]. The vehicle is practical, but again requires custom tooling to manufacture, and does not support an OTS replacement to the inflatable platform in the event of damage. Another vehicle, the Jetyak, provides similar capabilities and uses an OTS platform for flotation and propulsion, but is large, rigid, and must be transported inside a large vehicle, limiting its portability [18]. A vehicle that could provide most of the survey capabilities of existing vehicles while minimizing the issues they pose would be a valuable asset to groups with an interest in coastal monitoring.
VEHICLE DESIGN AND FABRICATION

GeoFF was designed with low cost and high usability as the top priorities. The design included mostly off-the-shelf (OTS) components, with the number of custom or difficult-to-fabricate parts minimized. The vehicle has electric propulsion, a real time kinematic (RTK) GNSS antenna and receiver, an OTS autopilot, and a single beam sonar echosounder. Floatation is provided by a lightly modified stand up paddleboard (SUP). Following construction, initial propulsion tests were conducted in indoor tanks, and maneuvering and sensor tests were performed at the URI Narragansett Bay Campus and nearby lakes. These tests showed that the vehicle can operate in environments of interest and that it collects useful data while doing so. After confirming its basic bathymetric survey function, the paddleboard USV was employed in several other surveys, cementing its utility. The experience of operating the vehicle in the field revealed its strengths and weaknesses, and analysis was performed to characterize its performance and identify system parameters.
MECHANICAL STRUCTURE

In the design process, usability considerations included both maximizing portability and minimizing the skill required to deploy the vehicle. Using an inflatable SUP simplifies transportation and deployment in rugged environments by reducing weight and bulk compared to a hard hull, such as a surfboard or kayak. The Freein 7’8” inflatable SUP provides displacement sufficient for almost 80 kilograms of payload, according to the manufacturer [19]. If necessary, increasing the allowable payload can be accomplished by replacing the existing SUP with a larger one, such as the Aqua Plus 10’6” model [20]. When deflated, the SUP and all other vehicle system components can fit in a compact passenger car as shown in Figure 1 rather than requiring a specialized rack or light truck for transport.

![Figure 1: Passenger car luggage area loaded with USV and equipment in preparation for a bathymetry survey](image)

The components for propulsion, guidance, and sensing are attached to a frame made of carbon fiber tubes instead of heavier metal alternatives, which also reduces weight. This CF frame folds for transport, reducing bulk in the same vein as the inflatable
paddleboard. It can be unfolded and secured for deployment using readily available hex keys so that no specialized tools are required. To fold, a small number of screw connections are loosened, and one fitting can slide down a CF frame member to allow the thruster struts to swing inward as shown in Figure 2, decreasing the structure’s outer dimensions.

![Figure 2: Top view of USV CF frame (a) unfolded for deployment, (b) folded for transport](image)

The GPS antenna is mounted to the central hexagonal plate. The SUP, CF structure, and all other components have a mass of approximately nine kilograms combined, not including the vehicle’s battery. This weight is easily carried in one hand, while the SUP can be packed in a backpack and a battery carried in the remaining hand. The battery adds an additional 12 kilograms for a total system mass of 21 kilograms.
While this structure proved to be durable overall, two FDM-printed plastic frame joints failed in the field after more than a year of use. These joints could be replaced with OTS metal brackets with drilled holes for additional strength, or the vehicle could use an entirely different architecture that eliminates the CF frame as discussed in the “Future Work” section below.

The frame is impermanently attached the SUP using 3M Dual Lock reclosable fastening strips bonded to both the SUP and frame with adhesive as shown in Figure 4. By spacing out the Dual Lock attachment points across the structure and providing a rigid backing for the strips where needed, the bond between the SUP and frame is very rigid, with little
relative motion between the two when connected. This attachment method requires no tools to use as the strips can be assembled and disassembled by hand. The battery box is attached in a similar fashion as shown in Figure 5. Combined, the inflatable SUP and folding CF frame form the basis of a highly portable yet rugged survey vehicle that is simple to deploy.

Figure 5: 3M Dual Lock mounting for the USV battery box
SENSING, NAVIGATION, AND ARCHITECTURE

Cost was also a major factor in the design of GeoFF. The electronics for control, navigation, and power delivery are all OTS components. They consist of a Cube Orange autopilot, FRSKY RC receiver, an ArduSimple simpleRTK2B GPS receiver with simpleSSR 4G RTK corrections, two Blue Robotics Basic electronic speed controllers (ESCs), and a Mauch PL-050 power monitor and PL 4-6S BEC (battery eliminator circuit). The autopilot uses ArduPilot Rover 4.1.0-beta1 open-source software for control and communication. These electronic components are housed in a commercial off-the-shelf (COTS) waterproof enclosure, with windows added for cable passthroughs. An RFD900x telemetry radio is used for communicating with the laptop computer base station, with its antennas mounted on an external fiberglass mast to maximize range. See Figure 6 for a system diagram of the vehicle showing connections between the components described above.

Figure 6: USV System Diagram
The cable passthroughs are sealed with Conta Clip KDS sealing elements pressed into two 3D-printed custom windows at either end of the enclosure.

![Figure 7: USV Electronics enclosure](image)

With these seals, the enclosure can withstand the wet environment it operates in. It is secured to the CF structure using stock U-bolts. The enclosure components can be manufactured with readily available equipment or ordered from established fabrication shops, allowing it to be easily replicated without extensive fabrication experience.

To provide useful scientific information, a Blue Robotics Ping single beam echosounder is also attached to the CF frame with a simple bracket. This sonar device allows the vehicle to measure up to 50 meters of water depth at a ping rate of up to 30 Hertz, with a range resolution equal to 0.5% of the measured distance [21, 22]. Cost and simplicity drove the selection of this sensor. It is easily integrated with the Cube Orange autopilot, has a low price, and is small enough to mount easily on the vehicle without greatly influencing its maneuvering properties. An additional package of water quality sensors, the YSI EXO2 sonde, was mounted to the bottom of the inflatable SUP without
tools in a manner similar to the CF frame. Two OTS metal pipe clamps equipped with Dual Lock strips secure it in place, and a pair of stainless-steel cables attached to the sonde and the SUP’s D-rings act as a failsafe (see Figure 8).

With the installed sensors, this sonde can measure temperature, conductivity, salinity, pH, turbidity, dissolved oxygen, and chlorophyll levels in the water, which are useful indicators of biological activity and water quality. The wide array of onboard sensors makes GeoFF useful both for mapping coastal bathymetry and monitoring the water itself, which was demonstrated over surveys discussed below.

Propulsion is provided by a pair of Blue Robotics T200 electric thrusters. These are the most economical option available for powering a vehicle of this size, costing
slightly more than 200 USD each at the time of this writing, and are readily available online [13]. The lateral separation between the two thrusters allows them to be used to provide differential thrust for yaw control, eliminating the need for a fragile rudder and servo steering mechanism. This steering method also enables the vehicle to turn in place at zero forward speed, improving maneuverability in restricted spaces. The geometry of the thruster mounting increases the lever arm by rotating the thruster out from the centerline, resulting in a lever arm of 0.495 meters as shown in Figure 9.

![Figure 9: Lever arms of thruster canted relative to centerline compared to thruster parallel to centerline](image)

Without this angle, the lever arm would be limited to the separation between the thruster and the center of mass, only 0.272 meters as modeled, representing a lever arm length increase of almost 82% without increasing the width of the vehicle.
To test the propulsion system, the time taken for the vehicle to traverse a fixed distance was measured with a stopwatch in a towing tank at several throttle settings. This measurement method was chosen because GPS was not available for speed measurement due to the surrounding building interfering with signal reception.

Current draw and battery voltage were measured using onboard telemetry. From these measurements, the power required for GeoFF to run at several fixed speeds was calculated and plotted in Figure 10. The resulting plot revealed the expected relationship between speed and power consumption, deviating slightly from cubic because of the vehicle’s tendency to rise out of the water at higher speeds. It also illustrated the power consumption penalty associated with running the vehicle above a speed of one meter per second. For surveys, range can be maximized by restricting speeds to this value or less. With this data, it is possible to select different batteries for different mission profiles. A small deep-cycle marine lead acid absorbed glass mat (AGM) battery should be able to support a three-hour mission with a track length of three kilometers while limiting total system weight to approximately fifty pounds. Weight can be reduced for the same range by instead using a lighter lithium polymer (LiPo) battery for model aircraft or boats.
Longer operations are possible by changing batteries between missions. Overall, the results of the propulsion tests showed that GeoFF could be suitably powered with a variety of existing batteries available from conventional sources, another important aspect of usability.
INITIAL TESTING

With a working vehicle constructed, real-world tests were performed to demonstrate its maneuvering, autonomous navigation, and surveying abilities. Initial maneuvering and navigation tests were performed from the GSO Beach at the URI Narragansett Bay Campus. In the first test, the vehicle was able to maneuver under remote control in the light surf present at the beach. A safety tether was used to prevent the vehicle from floating away in the event of control loss. Autonomous navigation was not operable in this test due to poor calibration of the autopilot’s internal magnetic compass. Once this issue was rectified, a later test at the GSO Beach (Figure 11) demonstrated that the vehicle was able to orient and propel itself towards given GPS waypoints.

![Figure 11: Joshua Wood handling safety tether during second test at GSO Beach (photo: Jessica McLaughlin)](image)

With this basic functionality verified, further testing was performed at Indian Lake in South Kingstown to tune the speed, steering, and navigation controllers of the
Cube Orange autopilot implemented in the ArduPilot firmware. GeoFF was programmed to follow a rectangular course in open water, its turning and course following performance were observed, and these observations used to adjust the gains in the control firmware. In these tests, telemetry data indicated that the GPS receiver and the autopilot’s inertial measurement unit (IMU) were correctly reporting the vehicle’s pose (position and attitude). However, extensive tuning across several testing sessions was unable to resolve the controller’s inability to maintain a heading or consistently navigate to a waypoint, especially in the presence of wind.

The navigation controller in ArduPilot uses an L1 controller. It uses a target on the intended vehicle path to compute a desired lateral acceleration that moves the vehicle towards this path [23]. This path is defined as a straight line between the vehicle’s original location and its intended destination. In the context of the ArduPilot firmware, these points are the vehicle’s previous and subsequent mission waypoints. A distance called \( L_1 \) is then defined along this path, which is measured starting from the point closest to the vehicle along the target path and a distance defined by Equation 1:

\[
L_1 = 0.3 \times damping \times period \times speed
\]

*Equation 1: Formula for \( L_1 \) distance used in navigation controller*

where damping and period are user-set parameters and speed is measured in-situ [24]. The controller then computes a desired lateral acceleration towards the intended vehicle track using Equation 2:

\[
Desired \text{ lateral acceleration} = \frac{4 \times damping^2 \times speed^2 \times \sin(v_1 + v_2)}{L_1}
\]

*Equation 2: Formula for desired lateral acceleration used in navigation controller*
where $\nu_1$ is the angle between the intended vehicle track and the line drawn from the vehicle to the point a distance $L_1$ ahead of the vehicle’s along-track point and $\nu_2$ is the angle between the vehicle’s velocity and its intended path. This desired acceleration is then used as the input for the turn rate controller, which is a PID loop that then outputs high-level motor commands in the form of “steering output” [24]. Separate from the navigation controller, the vehicle speed controller is an independent PID loop that attempts to make the vehicle speed track a setpoint based on throttle control and feedback from the GNSS receiver and IMU. The period and damping of the aforementioned navigation controller, along with the turn rate and speed controllers’ proportional, integral, and derivative gains, were the parameters adjusted during the tuning process based on observations of the vehicle behavior following documentation from the ArduPilot website [25].

![Indian Lake Controller Tuning](image)

*Figure 12: Vehicle path during tuning at Indian Lake*
Figure 12 shows the path taken by the vehicle during testing in Indian Lake before the controller issues were resolved. The intended path was a grid composed of straight lines, but the vehicle was unable to consistently maintain its heading, so the resulting path was curved. This issue was eventually resolved by upgrading the autopilot firmware to version 4.1.0-beta1 that included the ability to increase the turning moment achieved by the motor control library [26]. The original algorithm used by this library in Rover 4.0.0 scaled steering and throttle commands from the navigation and speed controllers to values between -1 and 1, summed them to a value between -2 and 2, then scaled them again by dividing both throttle and steering commands by this sum as in Equation 3 and Equation 4. The left motor would receive the sum of the resulting throttle and steering commands, while the right motor would receive their difference as computed in Equation 5 and Equation 6.

$$steering \text{ scaled} = \frac{steering}{steering + throttle}$$  
\textit{Equation 3: Computation of scaled steering command}

$$throttle \text{ scaled} = \frac{throttle}{steering + throttle}$$  
\textit{Equation 4: Computation of scaled throttle command}

left motor = throttle scaled + steering scaled  
\textit{Equation 5: Summing of throttle and steering commands to compute left motor command}

right motor = throttle scaled - steering scaled  
\textit{Equation 6: Difference of throttle and steering commands to compute right motor command}

The updated algorithm in Rover 4.1.0-beta1 modified the previous version. Instead of simply scaling the steering and throttle commands, the steering command was interpolated to a value between the reciprocal of the summed throttle and steering
commands and 1, where “mix” is a user-set parameter. This interpolated value was then multiplied by the original steering command (see Equation 7 and Equation 8).

\[
\text{scaler} = \frac{1}{\text{steering scaled} + \text{throttle scaled}}
\]

*Equation 7: Computation of scaler variable used in interpolation*

\[
\text{steering scaled} = \text{steering scaled} \times \left( \frac{\text{mix} - \text{scaler}}{1 - 0.5} \times (1 - \text{mix}) \times \text{mix} \right)
\]

*Equation 8: Interpolation of steering command*

The throttle command was then set to the difference between one and the absolute value of the resulting steering command as in Equation 9. The code computing the final throttle command also includes a check to set the throttle to forward or reverse based on the sign of the previously computed throttle scaled variable in Equation 4.

\[
\text{throttle scaled} = 1 - |\text{steering scaled}|
\]

*Equation 9: Computation of final throttle command*

These final throttle and steering values were then transmitted to the left and right motors as before in Equation 5 and Equation 6 [27]. Practically, this change meant that rather than rigidly setting the speed difference between the thrusters to execute a turn, the firmware allowed the throttle command to be reduced to bolster the steering command, effectively increasing the applied yaw moment beyond what the previous firmware would have commanded.

Figure 13 in the Surveys section shows the USV path following a larger grid pattern after the firmware upgrade, where it was able to follow straight paths even in the presence of wind. Following the firmware change, the vehicle was able to maintain its heading and perform turns reliably despite environmental disturbances. At this point, testing progressed to evaluating the vehicle’s surveying ability. The vehicle successfully performed several surveys at Indian Lake, Easton Pond, Rose Larissa Park, the Narrow
River, and the Castle Hill distributed sensing observatory including both bathymetry and environmental measurements.
SURVEYS

The first bathymetry survey was performed near the public boat launch at Indian Lake in South Kingstown, Rhode Island. This was a preliminary test to determine the USV’s suitability for other missions. Given that the depth of Indian Lake is known to be approximately six feet (1.8 meters) and relatively constant across its bottom, successfully mapping it would be a good indication of the vehicle’s ability to survey unknown locations.

Figure 13: Bathymetry survey of Indian Lake with depth below sonar transducer shown in color

Figure 13 shows the filtered results of this survey overlaid on a satellite image, with the scale extending to two meters and approximating the expected depth of the flat lake bottom. The filtering process removed outlier depth values, likely caused by close-range sonar returns saturating the sensor’s depth output, by setting all depth values to zero above a threshold of 2.25 meters. This threshold was chosen based on a histogram of the
depth data (Figure 14). Based on these results, it was determined that the vehicle’s bathymetric survey performance was sufficient to justify employing it on further missions.

Following the Indian Lake bathymetry test, several other sites were surveyed as well. To supplement simultaneous work by a group of undergraduate students, GeoFF was deployed again to acquire bathymetry data at Easton Pond in Newport, Rhode Island. In terms of total length and maximum distance from its launch point, this was the largest survey undertaken with this vehicle. The acquired depth data were downsampled so that the spacing along and between each transect were approximately equal, then processed using the triangulated irregular network (TIN) interpolation algorithm implemented in QGIS [28]. Figure 15 shows the acquired bathymetry after downsampling and interpolation plotted on top of a satellite image. This downampling and interpolation method was also employed on subsequent surveys.
At several points, the vehicle exited the range of its onboard telemetry and control radios. Even without radio connectivity, GeoFF proceeded to its preplanned waypoints. However, the vehicle became entangled in lily pads during one such radio outage and had to be removed from the pond manually. Similar green areas indicate the presence of such aquatic plants in the satellite background image in Figure 15. Even in this failure mode, the vehicle performed gracefully, as it could be easily separated into its principal components of SUP, frame, and battery on site and extracted on foot by a single operator a distance of approximately 500 meters along the reservoir embankment. Radio and entanglement issues may be resolved with hardware changes, including installing a more powerful telemetry radio and adding 3D-printed thruster guards. Later testing enumerated in Appendix A: RFD900x and 3DR Telemetry Radio Range Test confirmed the superior range performance of the RFD900x compared to the 3DR SiK radio that had been used.
up to that point, prompting a switch to the former. The survey data had little overlap with
the bathymetry acquired by the undergraduate group due to the limitations of the vehicle
they used, but the depths acquired in the overlapping area were similar, indicating that
GeoFF once again had captured realistic depth data.

As part of a collaboration with other institutions predicting harmful
cyanobacterial blooms (HCBs), GeoFF was used to acquire water quality data in the
Upper Pond of the Narrow River in Saunderstown, Rhode Island. This site provided a
noteworthy environment in which to collect water quality data, since the southern end of
the pond receives salt water from Narragansett Bay, while the northern end is fed by a
freshwater creek. The collaboration provided a YSI EXO2 Multiparameter Sonde with
sensors for temperature, conductivity, pH, dissolved oxygen, turbidity, chlorophyll, and
chloride.

![Figure 16: Plot of interpolated Narrow River Upper Pond temperature data in pseudocolor with vehicle track in red](image-url)
All sensors except the chloride were calibrated with the appropriate standards according to the manufacturer’s instructions (the chloride sensor required dehydrated table salt which was not available in the timespan when the sonde was available for use, so it was left uncalibrated). Water quality data acquired from the sonde were stored onboard and retrieved after the survey, which covered the northeastern third of the Upper Pond. The plots of these data are shown in figures Figure 16 and Figure 17. The sonar echosounder was also active and collected bathymetry data, with data plotted in Figure 18.

The pond’s bathymetry and the parameters monitored by the calibrated sensors were plotted on satellite images. Given the mixing of fresh and saltwater in the pond, it was expected that a gradient in several parameters would be present. This was observed in a number of sensor channels, especially temperature and conductivity. Water further from the freshwater creek was observed to be colder, which roughly overlapped with the area
of saltier water. This indicated that the water closer to the creek likely originated from this source. The depth near the center of the pond was found to be between 13 and 14 meters, which also matched expectations.

Figure 18: Plot of interpolated Narrow River Upper Pond bathymetry in pseudocolor with vehicle track in light blue

The beach at Rose Larisa Memorial Park in East Providence, Rhode Island was surveyed as well. This site was of interest due to its preexisting role as the subject of erosion control measures whose performance was monitored with photogrammetric aerial surveys performed by aerial drone [29]. The aerial surveys’ coverage only extended to the low tide line since they were performed at this time to maximize the area visible to the quadcopter camera (see Fig. 19).
To extend the reach of these surveys, GeoFF was used at high tide to survey an area that overlapped that of the aerial surveys but extended to several meters of water depth.
The vehicle successfully acquired bathymetry data on this mission, shown in Figure 20. It was also the first real-world test of GeoFF’s portability, since all of the equipment needed for the survey was carried by two people on foot from the parking area down a cliff to the survey area. In addition, this deployment demonstrated the USV’s ability to operate autonomously in waves while surveying. Wave heights were estimated at around 25 centimeters during the mission, and the vehicle did not capsize despite taking waves from the beam during several turns.

The final example of GeoFF’s utility was a bathymetry survey performed at the Castle Hill distributed sensing observatory deployed from the eponymous lighthouse in Newport, Rhode Island. A fiber optic distributed temperature sensor had been installed at this site to monitor water flowing through the East Passage of Narragansett Bay. The bathymetry of the seafloor under the observatory had been estimated before installation, but it was not known with accuracy. Data acquired during this survey was intended to improve the understanding of the shape of the fiber optic along the seafloor. The planned mission instructed GeoFF to survey from a point close to the lighthouse out to the end of the fiber optic, then return, a total of three times. Because of the high tidal flow rates at this location, the survey was scheduled to take place at slack tide, just after high tide.
when the flow rate would be minimal. The USV was deployed from the shoreline adjacent to the Castle Hill lighthouse and had to be transported on foot, with its support equipment, 400 meters over a small hill and down an exposed rock slope. The USV SUP and backup support SUP were inflated upslope and carried down to the water, with the air pump and its battery left at the inflation site to reduce weight while walking on the rocks. Care was taken to select a point that allowed safe launch with a nearby flat area for final vehicle assembly and setup. The vehicle was launched approximately 10 minutes after the published high tide, manually maneuvered to the mission start location, then began executing the preplanned mission. Partway through the mission, a commercial fishing vessel moved through the area at high speed, generating a large wake that necessitated taking manual control of the vehicle to orient it into the oncoming waves and minimize the possibility of capsizing. Following this diversion, the vehicle resumed the preplanned mission until completion. The depth along the given array location is plotted in Figure 22, and the entire survey bathymetry is plotted in Figure 23.

![Castle Hill Bathymetry](image)

*Figure 22: Depth along distributed sensor survey at Castle Hill*
The survey took less than 25 minutes to run after launch, including the diversion. Despite the large waves encountered, GeoFF still captured smooth bathymetry data. This is likely due to the 30-degree beamwidth of the echosounder. Upon inspecting the attitude data during the survey, the vehicle’s pitch and roll were never high enough to significantly affect the path length between the transducer and the seafloor. The bathymetry was passed to the researchers who deployed the distributed sensing observatory to use in their study.

![Figure 23: Plot of bathymetry along track acquired during survey of Castle Hill observatory](image)

In addition to the surveys already completed, bathymetry survey services have been offered to Marina Bay Docking in Wakefield, Rhode Island in exchange for providing a site for maneuvering trials.
MANEUVERING TRIALS

Over the course of the tuning, testing, and survey deployments, several observations about the vehicle’s maneuvering performance were made. As previously discussed, initial attempts to manually tune the navigation controller were hampered by the control firmware’s inability to output a sufficient turn command signal. While attempting to resolve this issue on the original firmware version, it was observed that the vehicle was unable to maintain a heading, especially in the presence of disturbances. When commanded to navigate to a waypoint, the vehicle traced a curved path until it reached the waypoint and initiated a turn. Following this perturbation in yaw, the vehicle’s track would diverge significantly from the intended path to the next waypoint. This issue was exacerbated by the presence of wind which would perturb the vehicle’s heading even when it was not commanded to turn. Following a wind disturbance, the vehicle’s track would diverge in a manner similar to its response following a commanded turn. This occurred even in flat water. From, this it was concluded that wind represented the largest environmental disturbance acting on the vehicle. However, given the yaw subsystem’s inability to converge to a heading even in calm conditions, it was not evident if this external forcing or the firmware represented a larger obstacle to the system’s controllability. After the firmware was upgraded from version 4.0.0 to 4.1.0-beta1, the version which first supported prioritizing steering over maintaining a set speed, it was eliminated as a contributor to this issue and the vehicle was able to follow a heading. This was previously detailed in the Testing section. Based on this change, it was expected that the USV could be represented using a planar hydrodynamic model.

The original objective of this research had two stages. First, develop a routine to identify parameters for a dynamic model of this vehicle, then create a controller based on
this model to ensure vehicle stability and eliminate tuning requirements. The efforts undertaken will form the foundation for a dynamic model that underpins such a model-based controller.

To identify a dynamic model of the USV, a review of existing system identification (ID) was performed. Dynamic models of similar vehicles have previously been identified by analyzing a variety of maneuvers. Two of the most common are zigzag and circle maneuvers [30]. These motions share the advantage of being simple to implement. While circles mainly serve to demonstrate the steady-state response of a vehicle to steering input, zigzags of sufficient length and produced by sufficiently robust steering commands will excite a dynamic response in addition to steady-state. Other previously used maneuvers include sinusoidal turn commands [31] and stepping through combinations of throttle and turn commands [32]. The zigzag maneuver was selected to evaluate this vehicle for its simplicity and because the presence of both dynamic and steady-state response phases was expected to illustrate the vehicle’s entire yaw response to steering input.

Much of the literature reviewed to prepare for the maneuvering trials focused on vehicles propelled by either a pivoting outboard motor or a single propeller with steering provided by a rudder. The zigzags generated in these maneuvering trials were achieved by setting the throttle to a constant value, then commanding a turn in open loop at the maximum allowed outboard or rudder angle [33]. This was done to produce a yaw rate signal that would be clearly distinguishable from noise. In the interest of obtaining a broad response range, both strategies were employed in this research. Since the vehicle lacked a rudder, the throttle and turn commands were translated by the autopilot into
throttle signals sent to each thruster speed controller. Both signals were supplied to the autopilot as pulse widths in microseconds to be fed to the thruster speed controllers equivalent to those output from the onboard RC receiver.

The motor speed controllers use a standard RC servo control signal as input, where square pulses are transmitted at 50 Hz with varying widths [34]. At zero throttle, both signals are centered at a pulse width of 1,500 microseconds. Full forward throttle is achieved at a maximum pulse width of 1,900 microseconds and full reverse throttle is at the minimum of 1,100 microseconds [35]. Steering commands have the same center, maximum, and minimum values, but the maximum and minimum values translate to maximum starboard and port turn commands respectively. To command a turn, the throttle signals sent to the port and starboard thrusters are varied by the autopilot based on mixing the received throttle and steering signals. Commanding a turn to starboard requires the starboard throttle setting to be lower than the port setting, while commanding a turn to port requires a port throttle setting lower than starboard. Trials were run with five sets of throttle and steering command combinations as enumerated in Table 1.

<table>
<thead>
<tr>
<th>Combination</th>
<th>Left Turn Command (μs)</th>
<th>Right Turn Command (μs)</th>
<th>Throttle (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1400</td>
<td>1600</td>
<td>1900</td>
</tr>
<tr>
<td>2</td>
<td>1300</td>
<td>1700</td>
<td>1900</td>
</tr>
<tr>
<td>3</td>
<td>1200</td>
<td>1800</td>
<td>1900</td>
</tr>
<tr>
<td>4</td>
<td>1400</td>
<td>1600</td>
<td>1700</td>
</tr>
<tr>
<td>5</td>
<td>1100</td>
<td>1900</td>
<td>1700</td>
</tr>
</tbody>
</table>

*Table 1: Throttle and Steering commands issued during maneuvering trials*

These command combinations were output by a Python script running on a Raspberry Pi 4, shown in Figure 24, operating as a companion computer and connected to one of the Cube Orange serial ports [36]. The script’s activity was controlled by the RC transmitter so that it could be engaged or disengaged remotely. Motion data, including
GNSS position, heading, yaw rate, and velocity, were recorded by the Cube Orange as part of its normal logging function.

![Figure 24: Raspberry Pi and auxiliary battery mounted in enclosure on paddleboard](image)

All maneuvering trials were conducted in Point Judith Pond in South Kingstown, Rhode Island. Figure 25 shows the vehicle in the pond during these trials. This site was chosen for its accessibility, low traffic, lack of surface ice, and ease of launch facilitated by a concrete boat ramp. The existing docks reaching into the waterway were also expected to enable simpler vehicle recovery in the event of a failure. The vehicle was launched into the pond and maneuvered manually to a position where it was not expected to collide with the aforementioned docks. The command script was then engaged to drive the vehicle in an open-loop zigzag. The maneuver would proceed until the script reached a prescribed number of ten commanded turns or it was manually disengaged to prevent a collision. The vehicle would then be repositioned under RC control, and the maneuver
would repeat to collect several trials at the same combination of throttle and steering settings. After several trials, the steering command setting would be modified, and a new set of trials executed. Trials were conducted with the vehicle oriented to a variety of initial headings in an attempt to eliminate effects from wind.

Following these maneuvering trials, the yaw rate and heading were examined to determine their suitability for computing hydrodynamic damping and added mass coefficients. Most of the zigzag trials exhibited significant drift in mean heading between the beginning and end of the trial, indicating the influence of an environmental disturbance. Out of a total of 24 trials conducted during the first deployment, only one zigzag maneuver was considered to be usable for coefficient estimation. This trial, referred to as the canonical trial, was used for computing hydrodynamic coefficients as described in the Analysis section. The vehicle was deployed for a second set of maneuvering trials at Point Judith Pond to collect more data that would be amenable to analysis. Subsequent inspection of the motion data logged during the second set of trials revealed that they included just as much drift as the first set, without contributing any
additional drift-free maneuvers. Qualitative observations made during both sets of maneuvering trials supported the previous observations made during tuning that the wind greatly influenced the vehicle’s yaw rate given its large surface area above the waterline. It was decided to pursue wind modeling to increase the applicability and validity of future models.

Previous attempts to explain the relationship between the vehicle yaw, wind speed, and wind direction were driven entirely by qualitative observations and were impeded by a lack of wind velocity data. To resolve this issue, a Calypso ULP ultrasonic anemometer [37] was mounted on top of the battery box. Instead of placing the wind sensor on top of a pole as recommended by the manufacturer, this mounting location was chosen to ensure that the device would measure wind actually experienced by areas of the vehicle that presented the largest face to the wind. It was connected to the autopilot and configured to log measured apparent wind and computed true wind based on vehicle orientation and speed.

A third set of maneuvering trials were executed at Point Judith Pond on a day with much higher wind speeds than any of the preceding trials. The zigzag maneuver proved to be infeasible due to the high wind speeds causing the vehicle to yaw rapidly as the wind changed speed and direction, especially when the force exerted by the wind applied a moment in the same direction as the moment applied by the thrusters.

Circle maneuvers were performed to collect data about steady-state yaw rates influenced by wind. Throttle and turn signals were commanded manually using the RC transmitter. In all subsequent trials, the throttle was kept at full while constant turns were commanded by keeping the transmitter’s steering joystick held at one of its mechanical
limits, then switching limits to command a turn in the other direction after performing as many rotations as possible while avoiding obstacles in the pond. Turns were discontinued to prevent collisions, to bring the vehicle closer to the RC transmitter, or to switch turn directions. The resulting turns were not truly circular since the yaw rate varied significantly as the vehicle presented a different area to the wind during different parts of the turn, while the forward speed remained relatively constant. This final set of trials concluded when two of the plastic frame joints failed while the vehicle was deployed, the available spares were depleted, and the vehicle had to be recovered by allowing the wind to blow it back to shore. These trials resulted in at least twelve turns amenable to analysis, which is described in the next section.
ANALYSIS

For the purposes of analyzing the vehicle’s motion, a coordinate system must be defined. In subsequent analysis, this right-handed body-fixed coordinate system originates at the vehicle center of mass and has axes $x, y,$ and $z$ oriented along the vehicle’s longitudinal, transverse, and vertical directions respectively (see Figure 26) [30].

Marine vehicles can move in six degrees of freedom (DOF, DOFs). Analyzing such a vehicle also requires defining rates of motion along and about the $x, y,$ and $z$ axes. The Society of Naval Architects and Marine Engineers (SNAME) convention for these rates defines linear velocities along the $x, y,$ and $z$ axes as $u, v,$ and $w$ respectively, with angular rates about these axes as $p, q,$ and $r$ [30]. The linear components are called surge, sway, and heave, while the angular components are referred to as roll, pitch, and yaw.
External forces and moments acting on the vehicle along the in \( x, y, z, p, q, \) and \( r \) directions are defined as \( X, Y, Z, K, M, \) and \( N \) respectively [30]. These definitions are summarized in Table 2.

<table>
<thead>
<tr>
<th>Description</th>
<th>Velocity</th>
<th>Force/Moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear x-axis motion</td>
<td>( u )</td>
<td>( X )</td>
</tr>
<tr>
<td>Linear y-axis motion</td>
<td>( v )</td>
<td>( Y )</td>
</tr>
<tr>
<td>Linear z-axis motion</td>
<td>( w )</td>
<td>( Z )</td>
</tr>
<tr>
<td>Rotation about x-axis</td>
<td>( p )</td>
<td>( K )</td>
</tr>
<tr>
<td>Rotation about y-axis</td>
<td>( q )</td>
<td>( M )</td>
</tr>
<tr>
<td>Rotation about z-axis</td>
<td>( r )</td>
<td>( N )</td>
</tr>
</tbody>
</table>

Table 2: SNAME coordinate system, velocity, and force/moment definition

The six forces and moments can be decomposed into components in the previously described directions to form a linearized model of vessel motion. These terms are composed of a velocity or acceleration in one of these directions multiplied by a mass or damping coefficient (see Equation 10) [30].

\[
X = X_u u + X_v v + X_w w + X_p p + X_q q + X_r r + X_u \dot{u} + X_v \dot{v} + X_w \dot{w} + X_p \dot{p} + X_q \dot{q} + X_r \dot{r}
\]

\[
Y = Y_u u + Y_v v + Y_w w + Y_p p + Y_q q + Y_r r + Y_u \dot{u} + Y_v \dot{v} + Y_w \dot{w} + Y_p \dot{p} + Y_q \dot{q} + Y_r \dot{r}
\]

\[
Z = Z_u u + Z_v v + Z_w w + Z_p p + Z_q q + Z_r r + Z_u \dot{u} + Z_v \dot{v} + Z_w \dot{w} + Z_p \dot{p} + Z_q \dot{q} + Z_r \dot{r}
\]

\[
K = K_u u + K_v v + K_w w + K_p p + K_q q + K_r r + K_u \ddot{u} + K_v \ddot{v} + K_w \ddot{w} + K_p \ddot{p} + K_q \ddot{q} + K_r \ddot{r}
\]

\[
M = M_u u + M_v v + M_w w + M_p p + M_q q + M_r r + M_u \ddot{u} + M_v \ddot{v} + M_w \ddot{w} + M_p \ddot{p} + M_q \ddot{q} + M_r \ddot{r}
\]

\[
N = N_u u + N_v v + N_w w + N_p p + N_q q + N_r r + N_u \ddot{u} + N_v \ddot{v} + N_w \ddot{w} + N_p \ddot{p} + N_q \ddot{q} + N_r \ddot{r}
\]

Equation 10: 6 DOF linearized marine vehicle dynamic model

The model can be simplified by reducing the number of degrees of freedom from six to three. This change eliminates three equations and half of the terms from each of the remaining equations (see Equation 11).

\[
X = X_u u + X_v v + X_r r + X_u \dot{u} + X_v \dot{v} + X_r \dot{r}
\]

\[
Y = Y_u u + Y_v v + Y_r r + Y_u \dot{u} + Y_v \dot{v} + Y_r \dot{r}
\]
\[ N = N_u u + N_v v + N_r r + N_u \dot{u} + N_v \dot{v} + N_r \dot{r} \]

*Equation 11: 3 DOF linearized marine vehicle dynamic model*

The resulting 3 DOF model is also referred to as a horizontal plane model, and represents a surface vehicle which can move in surge, sway, and yaw, with no vertical, pitch, or roll motion [30]. While the 6 DOF and 3 DOF model definitions provide detailed descriptions of marine vessel motion, not all six or three degrees of freedom are necessary to represent decoupled portions of a vessel’s motion. The model order can be reduced to 1 DOF, representing motion of a vehicle in only a single axis. For simplicity, this type of model was selected to represent the vehicle’s yaw subsystem. The resulting 1 DOF model consists of a single equation with two terms (see Equation 12).

\[ N = N_r r + N_r \dot{r} \]

*Equation 12: 1 DOF linearized yaw model*

In this model, \( N \) represents the thruster moment applied to the vehicle, \( N_r \) is a damping coefficient, and \( N_r \) is a rotational inertia coefficient. The latter two terms are determined by the vehicle’s mass and hydrodynamic effects, and must be identified in order to use this model for predicting the vehicle’s yaw response to thruster input.

It was decided to focus on yaw because of the difficulties previously encountered while tuning the autopilot’s navigation controller. Arriving at a set of gains that reliably produced the desired vehicle speed required much less effort than doing the same for the control loops which determined the vehicle’s yaw rate commanded from a given heading error. In the interest of modeling for future controller development, determining the vehicle’s maneuvering response in yaw was considered to be the most important analysis goal. A linear regression was performed on the yaw rate and throttle data to compute the desired damping and added mass parameters. Once data from trials with the wind sensor
were acquired, they were also analyzed to build a relationship between vehicle yaw rate and relative wind. Given the low number of trials used in this analysis, the validity of the results is uncertain and could be improved through more testing.

The first step was to determine which trials were suitable for analysis. Motion data from the zig-zag trials were plotted with respect to time to manually inspect the executed maneuvers for suitability for use in computing the USV’s hydrodynamic coefficients. These data included compass heading, yaw rate, and PWM signals sent to the thruster speed controllers. Trials could be identified by inspecting the PWM signal inputs and resulting heading output. During trials, the alternating thruster commands appeared as a pair of square waves representing the alternating throttle signals sent to each speed controller, while the heading appeared as a sawtooth curve indicating the back-and-forth yawing motion of the vehicle. Trials where the peak or trough heading values drifted significantly over the course of the maneuver were considered unusable for analysis, since this drift implied the influence of an external force that could not be accounted for. Since the computation of the aforementioned coefficients depends on the assumption that only the vehicle’s propulsion tends to accelerate the vehicle, including these trials in the analysis would result in invalid coefficients. Using this criterion, only one of the zig-zag trials conducted was found to be of acceptable quality for analysis.

The usable trial occurred when the steering and throttle signals yielded a zigzag generated by alternately setting one thruster to full throttle with the other at 50% throttle for five seconds. It consisted of nine turns in total.
While even this trial exhibited some drift, it was held to one degree or less from turn to turn. To confirm the straightness of this trial, GNSS position data was plotted to visualize the path of the vehicle during the maneuver. Based on this inspection, it was decided to proceed with analyzing this trial.

Once the usable trial was isolated from the acquired data, the throttle data from this trial was converted to applied moment. It was assumed that a thruster running at full throttle produced its full rated forward thrust of 3.71 kgf (36.38 N), while the thruster at 50% produced 0.84 kgf (8.24 N) as specified by the manufacturer. As discussed later, this assumption is likely not accurate due to the thrust rating coming from measurements of a stationary thruster performing a bollard pull rather than a moving thruster. In this application, the thrust is applied at an angle to the vehicle’s centerline due to the thruster mounting described in the vehicle design section. Since the usable trial commanded the running thruster to full throttle, the full thrust rating was multiplied by the effective lever
arm to produce the moment applied to the vehicle by the thrusters during a turn. The coordinate system used in calculations is located at the vehicle center of mass. The x-axis in this system points towards the bow, the y-axis points to starboard, and the z-axis points down. Applied moments \( N \) about \( z \) are positive when they tend to yaw the vehicle to starboard, while negative applied moments cause turns to port.

Two methods were employed to compute the desired coefficients. The first was linear regression. For this method, the yaw rate \( r \) was first differentiated with respect to time to find the acceleration in yaw \( \dot{r} \). Using the yaw rate, yaw rate time derivative, and applied moment data from the usable trial, a linear regression was performed to compute the hydrodynamic damping and added mass coefficients in yaw using the setup below in Equation 1, where the variables \( r, \dot{r} \), and \( b \) are vectors containing the samples of yaw rate, yaw acceleration, and applied thruster moment respectively that were acquired during the trial or computed afterward. The system was then solved for \( \bar{x} \) to find the values of \( N_r \) and \( \dot{N}_r \). The regression method yielded \( N_r = 122.45 \text{ kg} \cdot \text{m}^2 \cdot \text{s}^{-1} \) and \( \dot{N}_r = 7.86 \text{ kg} \cdot \text{m}^2 \).

\[
A = [r, \dot{r}], \quad \bar{x} = [N_r, \dot{N}_r], \quad b = N_{\text{thrusters}}, \quad Ax = b
\]

Equation 13: Setup for hydrodynamic coefficient linear regression

In addition to the coefficients computed using regression, an additional method of computing the hydrodynamic damping coefficient were employed for comparison. This consisted of simply dividing the absolute value of the mean moment applied during the trial by the mean of the absolute value of the yaw rate observed during the trial as shown in Equation 2. Taking the absolute value eliminated any effects from the vehicle switching direction, as it ensured that all input values would be positive. This method assumed that the dynamic segments between turns of opposite direction were of zero
length in time. Given that the dynamic segments were consistently less than 0.5 seconds in length out of a total of five seconds per turn, this assumption is acceptable.

\[ N_r = \frac{\text{mean}(|N_{\text{thrust}}|)}{\text{mean}(|r|)} \]

*Equation 14: Mean method for calculating hydrodynamic damping coefficient*

For the trial under evaluation, this resulted in \( N_r = 127.63 \text{ kg.m}^2\text{s}^{-1} \). However, this method does not produce a value for \( N_r \). Given the basic simulation results presented below, it was determined that the regression result for \( N_r \) was sufficient and a more accurate value was not required.

After computing the hydrodynamic coefficients, a simple simulation of the vehicle’s yaw response was performed. Assuming that the vehicle’s yaw motion is generated solely by the thruster action, the yaw dynamics of the vehicle can be represented with Equation 3.

\[ \Sigma N = N_r \dot{r} = N_{\text{thrust}} - N_r r \]

*Equation 15: Rearranged USV yaw dynamics*

The yaw rate time derivative \( \dot{r} \) can be isolated by rearranging Equation 3 into Equation 4.

\[ \dot{r} = \frac{N - N_r r}{N_r} \]

*Equation 16: Rearranged USV yaw dynamics with yaw rate isolated on left-hand side*

In this case, the added mass coefficient \( N_r \) also includes the rigid body rotational inertia \( I_{zz} \) resulting from the vehicle’s mass distribution about the coordinate system origin.

Using this rearrangement and assuming zero initial yaw rate, a value of the yaw rate time derivative was calculated for each timestep for which an applied thruster moment sample existed. This yaw rate derivative was then integrated by multiplying it by the time step to obtain the yaw rate for that simulation time step. This simulation was run twice: once
with the coefficient values calculated using regression, and again using the regression-derived inertia term $N_r$ with the approximated hydrodynamic damping term $N_r$ obtained by dividing the applied moments by the measured yaw rate. The results of both of these simulations are plotted with respect to time in Figure 23, along with the vehicle heading and the average yaw rate measured by the vehicle’s three IMU gyroscopes.

The data acquired from the trial where the wind sensor was installed were also analyzed with the goal of correlating the wind experienced by the vehicle to the yaw rate achieved during a turn. Given the small number of trials and the incomplete coverage of wind speeds, it was not expected that a full wind model would be created from these data. However, creating a correlation between wind and yaw rate, effectively creating a performance envelope for the vehicle in yaw, was within the realm of possibility.
Similar to the zigzag trial analysis, the first step in analyzing the wind trials was to plot motion data from the entire deployment versus time, along with the apparent wind speed and direction. From inspecting this plot, shown in Figure 24, it was apparent which trials were of sufficient length for analysis and which were cut off after only a short time. In addition, some trials exhibited unusual behavior of the wind sensor where the apparent wind speed became fixed at a single value for an extended time period. These trials were excluded from further analysis. The vertical red and light blue lines in Figure 29 indicate the points in time when the usable trials start and end, respectively. Plotting the entire set
of acquired data also showed that the apparent wind speeds never fell below one meter per second during these trials.

For this reason, no relationship between wind conditions and yaw rate can be constructed that covers the range of apparent wind speeds down to zero. However, general statements can be made about the achievable yaw rate in given wind conditions.
Two methods were used to visually correlate the wind conditions to the achieved yaw rate. The first was to plot the motion and wind data from the usable trials on a polar plot (Figure 25), where apparent wind angle was on the theta axis, wind speed was on the radius, and yaw rate was plotted in color.

Note that turns to port have a negative yaw rate and are plotted in blue, while turns to starboard are positive and are plotted in yellow and green. The plot angle indicates the angle at which wind approaches the vehicle, with angles from zero to 180° indicating a wind from the starboard side, and angles from 180° to 359° representing winds coming from the port side.

The right half of the plot, representing winds from the starboard side, has notably more blue samples than the left half, indicating that the vehicle turns more quickly to port when the wind is assisting it from the starboard side. Similarly, the left half contains
significantly more green and yellow samples, showing that winds from the port side cause higher turn rates to starboard.

To provide more granular detail about the relationship between wind conditions and yaw rate, these data were also binned and plotted again. Binning was accomplished by dividing the wind data into four 90° quadrants, with each quadrant further divided into three 10° bins of apparent wind angle. After binning, yaw rate data in each bin was run through a 6th-order Butterworth filter with a cutoff frequency of 0.25 Hz. This cutoff frequency was selected based on the Fourier transform of the yaw rate data showing the highest magnitudes at frequencies below this threshold. A linear fit was performed on the filtered, binned yaw rate data, which was then plotted versus wind speed on a scatter plot. These plots are shown in Figures 33 through 35.

Figure 31 is a key to interpreting the first plot showing colors representing wind direction bins and line styles corresponding to vehicle turn directions.
Figure 31: Key to first wind figure interpretation. Solid/dashed lines indicate port/starboard turns respectively, while blue, yellow, and green colors correspond to winds from the front, front-right, and right.

Figure 32: Scatter plot of filtered yaw rate data vs. apparent wind speed from the front-left quadrant.
Figure 33: Scatter plot of filtered yaw rate data vs. apparent wind speed from the front-right quadrant

Figure 34: Scatter plot of filtered yaw rate data vs. apparent wind speed from the back-left quadrant
Figure 35: Scatter plot of filtered yaw rate data vs. apparent wind speed from the back-right quadrant

In these plots, starboard and port turns are plotted separately. Starboard turns are represented by open circles with the linear fits plotted as solid lines, while port turns are plotted as squares with dashed lines representing the linear fits. Since port turns were logged by the autopilot with negative yaw rates in the vehicle’s coordinate system, their values were negated so that all turns appear above the plots’ x-axes.
DISCUSSION

The goal of determining the vehicle’s maneuvering response in yaw was partially achieved. Analysis of the zigzag trials produced hydrodynamic damping and added mass coefficients that yielded a simulation able to track the real vehicle’s yaw behavior. The analysis of wind influence to this response was limited by the low amount and noisy nature of the acquired data.

Based on Figure 23, the simulated yaw response of the vehicle using the hydrodynamic coefficients was accurate. The steady-state yaw rate of 6.4 degrees per second computed from the regression coefficients is within 0.5 degrees per second of the mean absolute yaw rate of 6 degrees per second computed during the trial. The peak rotational acceleration computed from the trial data is 1.7°/sec², while the simulated peak value is 3.5°/sec². Although the simulated acceleration is faster, the dynamic turn phases are so short that this error does not significantly degrade the fidelity of the simulation. However, this result was obtained from only one trial, since there was only one zigzag maneuver among the trials performed that was considered usable. It is possible that better results could be obtained by performing more trials in low wind conditions. In addition, performing further non-zigzag maneuvers would allow the computed parameters to be validated against inputs other than those used to generate them. Another restriction of the system identification method is the assumption that the thrusters produce their rated output force at a given throttle setting at any speed. These thrust ratings were experimentally determined by the manufacturer in a bollard pull test, meaning that they were stationary relative to the water. In reality, the thrusters move with the vehicle relative to the water, reducing their thrust output as relative velocity increases, which the parameter computation method does not account for.
It is important to note that the planar hydrodynamic model used to represent the vehicle is limited to one forward speed. In this instance, this is the speed at which the vehicle was traveling during the trial used to compute the model parameters. Since the throttle was controlled rather than forward speed during the trials, this model speed can only be approximated for the generated parameters. Despite this, the relatively constant total thrust during the trial resulted in a steady forward speed as reported by the GNSS receiver. The vehicle’s forward speed during the trial is plotted in Figure 33, with the average trial speed of 1.4 meters per second denoted as a horizontal black line.

![Figure 36: Forward vehicle speed during maneuvering trial used to compute model parameters](image)

Based on this, the model speed is set at 1.4 meters per second. While this is fortunately close to the vehicle’s normal survey speed of one meter per second, more trials must be performed to compute model parameters at this speed.

Adding wind to the analysis of the vehicle allowed previously qualitative observations to be supported by measurements. The relationship between wind conditions and yaw rate was expected to be highly nonlinear: the moment exerted by the wind is dependent on both apparent direction and speed.
It was also expected that bins where the wind was assisting the turn by blowing directly from the port or starboard side would result in the highest achieved yaw rates. This is generally seen in the plots. For example, the dotted green line in Figure 26 represents port turns which occurred during winds blowing directly from 90° to starboard. This line is the highest linear fit in this figure, while the solid green line representing starboard turns at the same wind angle is the lowest. Wind from this angle resists starboard turns while assisting port turns. Similar trends can be seen in the other plots, but Figure 27 shows an exception. In this plot, the highest average linear fit is the solid yellow line representing starboard turns occurring during winds from -40° to -50°. The solid blue line is expected to be higher, since it represents starboard turns assisted by winds coming directly from port. Additionally, the port turns expected to be lowest, the dashed blue and yellow lines, are also swapped. It is possible that the low amount of data used to generate these fits contributed to this deviation from the expected behavior.

The plots produced highlighted the one of the main limitations of the wind data collected. There were not enough trials completed to fully relate wind conditions to yaw all the way down to zero speed. In addition, many of the trials were short in duration due to the vehicle drifting close to obstacles forcing the end of multiple maneuvers. Together these limitations leave significant gaps in the correlation between wind and yaw rate. These issues could be resolved by testing over multiple days with different wind conditions at a site with more maneuvering room.
FUTURE WORK

While the GeoFF USV fulfilled its purpose as a low-cost solution to the problem of acquiring coastal bathymetry and water quality data, more work can be done to expand its capabilities and the modeling of its maneuvering properties.

Several aspects of the vehicle hardware could be modified as possible improvements. The vehicle was designed using a rigid CF frame to mount most of the components. This was done to eliminate unconstrained cables connecting the thrusters, sensors, and antennas to the waterproof enclosure containing the electronics. However, the inclusion of this frame added significantly to the vehicle’s material cost. It was also the second-largest subsystem in terms of extent after the SUP, increasing the system’s bulk. Eliminating the frame would reduce the vehicle’s size, mass, and cost, further increasing its accessibility to novice users. Instead of relying on the frame for mounting these components, they could instead be mounted to the SUP directly using Dual Lock strips, with cables secured using strips along their length. This so-called “octopus” configuration could be fabricated from the existing GeoFF vehicle to evaluate its portability and performance.

During development, the magnetometer integrated into the Cube Orange autopilot presented obstacles to progress. Initially, poor calibration of this instrument prevented the vehicle from using its automatic navigation function. Even once this issue was resolved, the magnetometer was still subject to environmental disturbances, especially when operating from sites with steel-reinforced concrete present. While these problems were not insurmountable, the incorporation of heading calculated from two independent GNSS receivers in a moving baseline configuration would eliminate them entirely. In this arrangement, one receiver computes its own position, then acts as a reference for a
second receiver to compute its own position relative to the first within a few centimeters of accuracy [38]. The direction of the vector drawn between these two positions is the vehicle heading, which is not subject to magnetic disturbances. The receiver currently installed on GeoFF does not support both RTK-corrected position and moving baseline heading computation, but receivers with this capability do exist [39]. Replacing the existing GNSS receiver with one that is moving-baseline capable would increase GeoFF’s robustness and add a level of redundancy to the determination of its heading.

In addition to hardware improvements, expanding the vehicle dynamic model from one to three degrees of freedom would be a valuable addition to existing work. Incorporating wind effects would further increase the model’s utility for model-based control. Previous work has presented the basis of a system identification method for generating the parameters of a 3 DOF dynamic model [33]. Creating a similar model would necessitate performing more maneuvering trials to observe the vehicle’s response to input in multiple axes. Integrating wind forcing into such a model was described by Fossen and requires measurement of the speed and direction of the wind acting on the vehicle, the computation of frontal and lateral projected vehicle areas, and the generation of nondimensional area-based coefficients [30]. Qu presented an implementation of such a model as part of a feedforward station keeping controller for a USV, noting that wind models for vehicles of this size are poorly documented in existing literature [40]. GeoFF already possesses an anemometer capable of reporting wind speed and direction at a high rate but developing a model capable of translating measured wind conditions to estimated forces exerted on the vehicle would enable the creation of a feedforward navigation controller to enhance the vehicle’s performance in varying wind conditions.
CONCLUSION

The GeoFF vehicle was designed to be a simple tool for surveying coastal areas, increasing the number of situations where such surveys are realistic. With a BOM cost of $3,500, total mass of 20 kilograms, and two-person operation, it achieved its design goals of low cost, portability, and ease of operation, and demonstrated its capabilities over the course of several surveys. The data acquired using GeoFF included both bathymetry and a range of water quality parameters, in conditions with varying disturbances from wind and waves.

Quantifying the true cost of such a vehicle beyond the cost of materials alone for comparison to existing solutions is difficult given varying costs of engineering and manufacturing labor. Its main advantages for potential users with low funding are the ease of replication, availability of requisite materials, and reliability. The hardware components that make up GeoFF are available for sale to the public and necessary software packages are freely available online. Given unsophisticated fabrication facilities, an interested researcher with a need for coastal observation capabilities could duplicate such a vehicle. In addition, the vehicle produced for this project performed reliably after resolving the early issues with compass calibration and firmware suitability. After solving these problems, it suffered no unrecoverable failures during survey operations. Following a year of field operations, two of the 3D-printed frame joints failed in quick succession. This part could be replaced in the field within five minutes. With proper pre-deployment inspection or replacement of these parts with more durable alternatives, the vehicle reliability could be increased further.

Analysis of the vehicle’s maneuvering properties was also successful but was not complete enough to form a comprehensive model of the vehicle including its full
response to wind. From one zigzag trial, the hydrodynamic damping and added mass coefficients were calculated, with subsequent basic validation indicating their values to be accurate. Wind modeling consisted of visualizations illustrating the relationship between wind conditions and yaw rate. These plots generally confirmed the qualitative observations which had suggested the strong wind influence exerted on the vehicle and provided some indication of the dependence on wind direction and speed.

Future work could expand the capabilities of the vehicle by simplifying the mechanical design and increasing the vehicle’s robustness. Performing more maneuvering trials with wind measurements would also allow the creation of a true dynamic model of the vehicle including this important environmental disturbance.
APPENDICES

Appendix A: RFD900x and 3DR Telemetry Radio Range Test

The RFD900x and 3DR telemetry radios were compared to determine their suitability for use on GeoFF. This test was performed by connecting one modem each radio pair to the Cube Orange autopilot installed in the vehicle, with the other modem connected to the ground control computer running Mission Planner. The computer was then used to connect to the autopilot using the connected telemetry radio and was then moved a range of distances from the stationary vehicle, which were measured in Mission Planner. Signal strength as a percent and received signal strength indication (RSSI) in dB were recorded for each distance. These data are presented in Figures XXXX and XX, where it is evident that the signal strength of the RFD900x decreased at a much lower rate with distance compared to the 3DR radio. Its RSSI was also consistently higher at all ranges.

![Signal Strength vs. Range](image)

*Figure 37: Plot of observed signal strength as a function of range for both the RFD900x and 3DR radios*
Figure 38: Plot of RSSI as a function of range for both the RFD900x and 3DR radios
Appendix B: Component costs

The prices listed in Table 3 below are in USD and are current as of June 2021.

DragonPlate carbon fiber tubes and associated fittings are not included.

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUP</td>
<td>1</td>
<td>$239.00</td>
</tr>
<tr>
<td>FrSky X8R Receiver</td>
<td>1</td>
<td>$37.80</td>
</tr>
<tr>
<td>Cube Orange</td>
<td>1</td>
<td>$208.00</td>
</tr>
<tr>
<td>Cube Mini Carrier Board</td>
<td>1</td>
<td>$52.00</td>
</tr>
<tr>
<td>Cube cable set</td>
<td>1</td>
<td>$15.00</td>
</tr>
<tr>
<td>RFD900x-US Telemetry Bundle</td>
<td>1</td>
<td>$229.00</td>
</tr>
<tr>
<td>GPS2 Cable</td>
<td>1</td>
<td>$4.00</td>
</tr>
<tr>
<td>Mauch PL-050</td>
<td>1</td>
<td>$34.60</td>
</tr>
<tr>
<td>Mauch PL-2-6s BEC</td>
<td>1</td>
<td>$71.54</td>
</tr>
<tr>
<td>arduSimple simpleRTK2B</td>
<td>1</td>
<td>$276.85</td>
</tr>
<tr>
<td>arduSimple 4G NTRIP Client</td>
<td>1</td>
<td>$214.38</td>
</tr>
<tr>
<td>Blue Robotics Basic ESC</td>
<td>2</td>
<td>$27.00</td>
</tr>
<tr>
<td>Blue Robotics T200 Thruster</td>
<td>2</td>
<td>$179.00</td>
</tr>
<tr>
<td>Blue Robotics Ping Sonar</td>
<td>1</td>
<td>$279.00</td>
</tr>
<tr>
<td>10” SMA Cable for GPS</td>
<td>1</td>
<td>$18.83</td>
</tr>
<tr>
<td>TNC-SMA adapter</td>
<td>1</td>
<td>$8.54</td>
</tr>
<tr>
<td>6 conductor cable</td>
<td>1</td>
<td>$11.37</td>
</tr>
<tr>
<td>3 conductor cable</td>
<td>1</td>
<td>$43.04</td>
</tr>
<tr>
<td>Bergquist TIM</td>
<td>1</td>
<td>$56.05</td>
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<tr>
<td>Conta clip grommets 2x4-5mm</td>
<td>4</td>
<td>$3.00</td>
</tr>
<tr>
<td>Conta clip grommets 2x6.5mm</td>
<td>4</td>
<td>$3.75</td>
</tr>
<tr>
<td>Conta clip grommets 2x5-6mm</td>
<td>4</td>
<td>$3.00</td>
</tr>
<tr>
<td>Conta clip grommets blank</td>
<td>4</td>
<td>$2.16</td>
</tr>
<tr>
<td>Conta clip grommets 2x4-5mm</td>
<td>4</td>
<td>$3.00</td>
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<tr>
<td>Conta clip grommets 1x2-3mm</td>
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<tr>
<td>25ft of 1” Black Dual Lock with VHB adhesive</td>
<td>1</td>
<td>$91.25</td>
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<tr>
<td>O-rings</td>
<td>1</td>
<td>$13.77</td>
</tr>
<tr>
<td>1” Aluminum bar for thruster bracket</td>
<td>1</td>
<td>$4.20</td>
</tr>
<tr>
<td>M3x12 FHPD, 316 SS</td>
<td>1</td>
<td>$8.33</td>
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<tr>
<td>M3 thin hex nut, 316 SS</td>
<td>1</td>
<td>$9.35</td>
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<tr>
<td>M3 male-female standoff, 8mm, AL</td>
<td>10</td>
<td>$1.50</td>
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<tr>
<td>M3x8mm SCHS, 316 SS</td>
<td>1</td>
<td>$11.36</td>
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<tr>
<td>M3 Nylock, 316 SS</td>
<td>1</td>
<td>$4.75</td>
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<tr>
<td>1/4”-20x1.25” SHCS, 316 SS</td>
<td>1</td>
<td>$6.20</td>
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<tr>
<td>M3x10 FHPD, 316 SS</td>
<td>1</td>
<td>$7.62</td>
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<tr>
<td>1/4”-20 hex nut, 316 SS</td>
<td>1</td>
<td>$7.17</td>
</tr>
<tr>
<td>5/8”-11x3/4” Hex head screw</td>
<td>1</td>
<td>$1.51</td>
</tr>
<tr>
<td>Group U1 AGM Battery</td>
<td>1</td>
<td>$120.68</td>
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<tr>
<td>2-5/8” ID Vibration damping routing clamp</td>
<td>2</td>
<td>$48.42</td>
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<tr>
<td>Battery box</td>
<td>1</td>
<td>$13.84</td>
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<tr>
<td>Aluminum offset surface bracket</td>
<td>1</td>
<td>$1.55</td>
</tr>
<tr>
<td>Aluminum corner bracket</td>
<td>2</td>
<td>$7.24</td>
</tr>
<tr>
<td>WC-25F Outdoor Enclosure with Clear Cover</td>
<td>1</td>
<td>$30.48</td>
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<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>$2,403.21</strong></td>
</tr>
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*Table 3: GeoFF USV component costs in USD*
## Appendix C: Electronic Component Power Draw

<table>
<thead>
<tr>
<th>Component</th>
<th>Current (A)</th>
<th>Voltage (V)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cube Orange [9]</td>
<td>0.550</td>
<td>5</td>
<td>2.75</td>
</tr>
<tr>
<td>ArduSimple simpleRTK3B [41]</td>
<td>0.120</td>
<td>5</td>
<td>0.6</td>
</tr>
<tr>
<td>FrSKY X8R RC Receiver [42]</td>
<td>0.100</td>
<td>5</td>
<td>0.5</td>
</tr>
<tr>
<td>RFD900x Radio [43]</td>
<td>1</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Blue Robotics Ping Sonar [21]</td>
<td>0.100</td>
<td>5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

*Table 4: USV GeoFF electronic components power draw*
## Appendix D: Blue Robotics Ping Sonar specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. supply voltage</td>
<td>5.5 V</td>
</tr>
<tr>
<td>Min. supply voltage</td>
<td>4.5 V</td>
</tr>
<tr>
<td>TTL voltage level</td>
<td>3.3-5.5 V</td>
</tr>
<tr>
<td>Typical current draw</td>
<td>0.1 A</td>
</tr>
<tr>
<td>Signal protocol</td>
<td>TTL Serial (UART)</td>
</tr>
<tr>
<td>Available baud rates</td>
<td>115200, 9600 bps</td>
</tr>
<tr>
<td>Acoustic frequency</td>
<td>115 kHz</td>
</tr>
<tr>
<td>Beamwidth</td>
<td>30 degrees</td>
</tr>
<tr>
<td>Range resolution</td>
<td>0.5% of range</td>
</tr>
<tr>
<td>Pressure rating</td>
<td>300 meters</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>0-30°C</td>
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</table>

*Table 5: Blue Robotics Ping sonar technical specifications [21]*
### Appendix E: Blue Robotics T200 Thruster specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Full throttle forward/reverse thrust @ 12 V</td>
<td>3.71/2.9 kgf</td>
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<tr>
<td>Minimum thrust</td>
<td>0.02 kgf</td>
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<tr>
<td>Operating voltage</td>
<td>7-20 V</td>
</tr>
<tr>
<td>Full throttle current @ 12 V</td>
<td>16.91 A</td>
</tr>
<tr>
<td>Full throttle power @ 12 V</td>
<td>200.9 W</td>
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</tbody>
</table>

*Table 6: Blue Robotics T200 thruster technical specifications [35]*
Appendix F: Cube Orange specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processor</td>
<td>ST Microelectronics STM32H753</td>
</tr>
<tr>
<td>Flash memory capacity</td>
<td>2 MB</td>
</tr>
<tr>
<td>RAM capacity</td>
<td>1 MB</td>
</tr>
<tr>
<td>Barometer</td>
<td>TE Connectivity MS5611</td>
</tr>
<tr>
<td>IMU</td>
<td>TDK ICM20602, ICM 20948</td>
</tr>
<tr>
<td>Supply Voltage</td>
<td>4.5.7 V</td>
</tr>
<tr>
<td>Current Draw</td>
<td>550 mA</td>
</tr>
<tr>
<td>Max. Current Draw (peripherals)</td>
<td>2.5 A</td>
</tr>
</tbody>
</table>

*Table 7: Cube Orange autopilot technical specifications [9]*
Appendix G: Calypso ULP Ultrasonic Anemometer specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply voltage</td>
<td>3.3-18VDC</td>
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<tr>
<td>Current draw</td>
<td>&lt;0.25 mA</td>
</tr>
<tr>
<td>Wind speed range</td>
<td>0-45 m/s</td>
</tr>
<tr>
<td>Wind speed accuracy</td>
<td>+/-0.1 m/s at 10 m/s</td>
</tr>
<tr>
<td>Wind direction range</td>
<td>0-360°</td>
</tr>
<tr>
<td>Wind direction accuracy</td>
<td>+/-1°</td>
</tr>
<tr>
<td>Sample rate</td>
<td>0.1 Hz to 10 Hz</td>
</tr>
<tr>
<td>Data output format</td>
<td>NMEA0183</td>
</tr>
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</table>

*Table 8: Calypso ultrasonic anemometer technical specifications [37]*


[40] H. Qu, "Wind Feedforward Control of a USV," Florida Atlantic University, Boca Raton, 2016.
