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Development of a New Lagrangian Float for Studying Coastal Marine Ecosystems

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Development of a new Lagrangian float for studying coastal marine ecosystems

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***Abstract*— This paper presents an overview and initial testing results for a shallow water Lagrangian float designed to operate in coastal settings. The presented effort addresses the two main characteristics of the shallow coastal environment that preclude the direct of use of many successfully deep water floats, namely the higher variation of water densities near the coast compared with the open ocean and the highly varied bathymetry. Our idea is to develop a high capacity dynamic auto-ballasting system that is able to compensate for the expected seawater density variation over a broad range of water temperatures and salinities while using measurements of both pressure and altitude above the bottom. The major components of the float consist of a Netburner micro processor, rechargeable lithium ion battery system, piston style volume changing mechanism, sensors for pressure and altitude, and a safely system for recovery and emergency conditions. Results are presented for field tests that verify the performance of the float for a variety of behaviors that are of general utility for both water tracking an profile sampling.**

***Index Terms*— float, drifter, sensor platform**

I. Introduction

The coastal marine environment represents not only a complex ecosystem but also an important commercial resource. In order to understand the natural dynamics and the affect of anthropogenic stresses in the coastal environment it is necessary to observe the interaction between the biological, chemical and physical processes which are linked both in space and time. Consequently, understanding the circulation of water in the environment is one of the critical pieces for evaluating the health of the coastal ecosystem.

One approach to study circulation is to use static environmental sensors and combine the collected data with computer models to simulate water exchange. However, as the important biological and chemical processes are coupled both spatially and temporally, a complete understanding is difficult to obtain in this point sampling manner when significant dynamics and structure exists at scales less than a kilometer.

An alternative way to explore these regions would be having sensors that drift with the water and directly track its motion through the environment while performing a variety of data collection behaviors. Autonomous Lagrangian floats are designed to do precisely this and are highly effective sensor platforms for many studies in the open ocean [1], [2], [3], [4]. More recently, smaller actively ballasted prototypes have been developed to sample the upper ocean $(< 100\mathrm{m})$ [5], [6] or perform alternating profiles and bottom stationing in shallow water [7]. Direct application of these floats for operation in coastal areas however is not immediate. The coastal areas, such as bays and river mouths, contain significant water density changes that will preclude some of the precise ballasting requirements of deep water floats and their volume changing capacity. For example, a section in upper Narragansett Bay, Rhode Island (Figure 1) shows that over a 20 km reach where water depth is ~ 12 m, the density varied by 5 kg m^{-3}, the temperature by 2.5 °C , and the salinity by over 5 psu. These gradients are far larger than would be encountered in the open ocean, but are not uncommon in a shallow water environment.

Additionally, deep water and upper ocean floats do not directly measure height above the bottom and would not be able to operate successfully in areas of highly varied bathymetry. These limitations suggest there is utility in exploring the

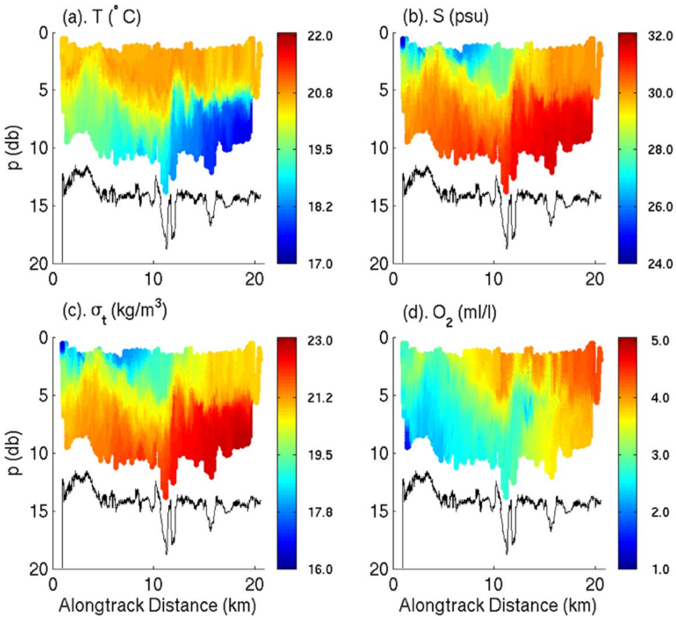


Fig. 1. Fine-scale hydrographic section along the axis of upper Narragansett Bay, Rhode Island, presented as a typical estuarine environment with a rich property structure. The black line is the bottom.

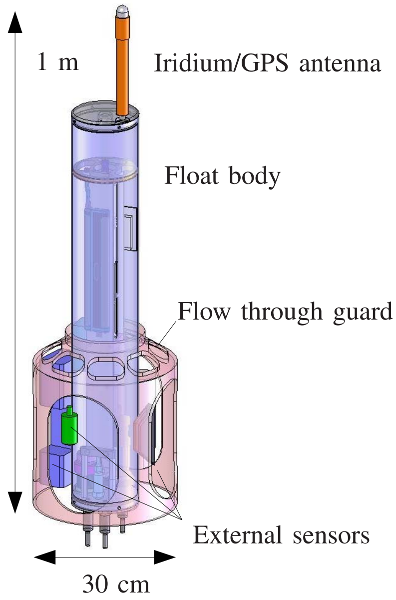


Fig. 2. Initial CAD model of the float. The cylindrical float body contains the majority of the components and additional external sensors can be mounted under a flooding guard and cabled into the body.

concept of small floats with large displacement capacity and sensors to measure altitude for working near shore.

Our prototype concept is shown in figure 2. The float is designed to operate in water depths from 2 to 100 meters. It is relatively small, easy to deploy and can support a variety of scientific sensors.

This paper continues to explain the major design considerations for the float in section II. Results from field tests in a local bay are presented in section III. Section IV summarizes the tests and comments on future developments.

II. Design

Our design of the shallow water float departs from several of the main attributes of current open ocean floats [8], [4], [9]. Our anticipated mission duration in the coastal area will be significantly shorter, days and weeks, compared with multi-year open ocean deployments. Thus our power budget is not optimized for very low hotel power and we anticipate more dynamic shorter missions where the majority of the energy will go directly into volume actuation against hydrostatic pressure. We have also considered the need for recovery, recharging and fast retasking of the float in a dynamic environment. Lastly, given our shallow depth rating and operating environment we can avoid the complication of compressibility matching with either the pressure case design or compressable members that have been used on several successful isopycnal floats [10], [11], [12].

A. Physical

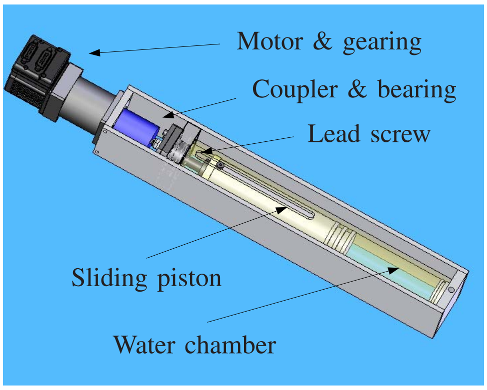
The float is built around a piston style volume changing mechanism, figure 3(a). The initial design concept was simulated in Matlab considering the basic acting forces of buoyancy, gravity, linear and quadratic drag and added mass. The simulations allowed us to design a buoyancy actuator to achieve profiling speeds up $20\mathrm{m}/\min$ and settling times of $\mathcal{O}(10's)\,\mathrm{sec}$. To move the piston a $110\mathrm{W}$ DC brushless SmartMotor by Animatics [13] was chosen. This motor contains its own internal programmable microcontroller and allows for easy implementation of calibration functions, digital PID motor position control and status monitoring. Although the motor is rated to $110\mathrm{W}$ of peak power, under typical operation is it significantly lower, typically $10\mathrm{W}$ or less.

The total variable volume change of $300\mathrm{cm}^3$ was chosen to compensate for the range of water densities the float may encounter and enough margin to lift the Iridium/GPS antenna out of the water for good communications while at the surface, figure 3(b). Although the Iridium antenna is relatively large the smaller options of ORBCOMM and ARGOS are likely to have either slow data rates or imprecise position fixes for efficient recovery of the float in the coastal environment, where currents can be quite strong and good tracking will be required to find it. Inside the float the actuator is positioned with the water chamber on top and plumbed to the bottom endcap. This allows the piston to purge air easily.

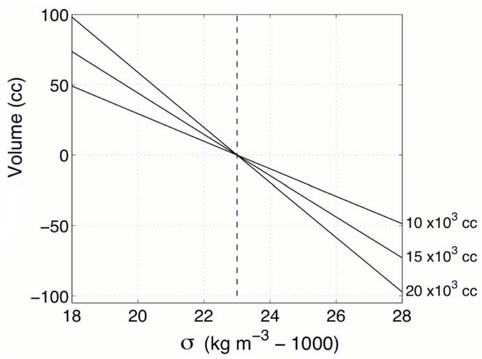
Overall, the float has a cylindrical shaped aluminum pressure housing $90\mathrm{cm}$ long with a diameter of $15.2\mathrm{cm}$. The two main constraints for the housing were that it fit all anticipated equipment and provide enough displacement to float the components and sensor payload when submerged. The tube size was calculated to carry equipment with a total mass of $16\mathrm{kg}$, including a $1\mathrm{kg}$ emergency drop weight and $2.5\mathrm{kg}$ of additional sensor weight. The aluminum housing was chosen to meet the pressure requirements for operation up to $100\mathrm{m}$. Given the shallow operating depth a simple $\frac{1}{8}inch$ wall cylinder is easily sufficient. Some plastic tubes could be used for the radial stress levels but would fail in buckling at this length. Additionally, given the capabilities of the new dynamic buoyancy system there is no need to match the compressibility of the housing to that of seawater, as is done with some deep water floats. Other considerations were cost, strength, ruggedness, and corrosion. The ends of the cylinder are closed with two ring sealed end caps. Figure 4 shows a picture of the lower end cap with sensors and bulkheads.

The float currently has a low cost pressure sensor [14] to measure pressure depth to $.1\%$. To measure height above the bottom an $225\mathrm{kHz}$ acoustic altimeter [15] is used. This sensor has a practical altitude operating range between one and 50 meters. These sensors allow for closed loop control of either depth or altitude, and more generally any position in the water column. The float is able to perform vertical profiles, constant depth or altitude drifts and tasks like, maintaining the mid water column depth as the total water depth varies.

Although the pressure sensor and altimeter have built-in temperature sensors they are not high quality measurements and suffer from significant thermal inertia. The next revision of the float will support an NBOSI CTD sensor for scientific quality measurements [16]. The higher quality CTD sensor will



(a)



(b)

Fig. 3. (**a**) Conceptual design of the volume changer with primary parts labeled. **b**) Volume-changer capacity required to maintain the float's neutral-buoyancy over a range of water densities. The dashed line is the assumed initial density of the float and the $10 - 20 \times 10^3$ lines indicated different float volumes. The range of water density represents the change from the lightest (warmest-freshest) to the heaviest (coldest-saltiest) water the float is likely to encounter.

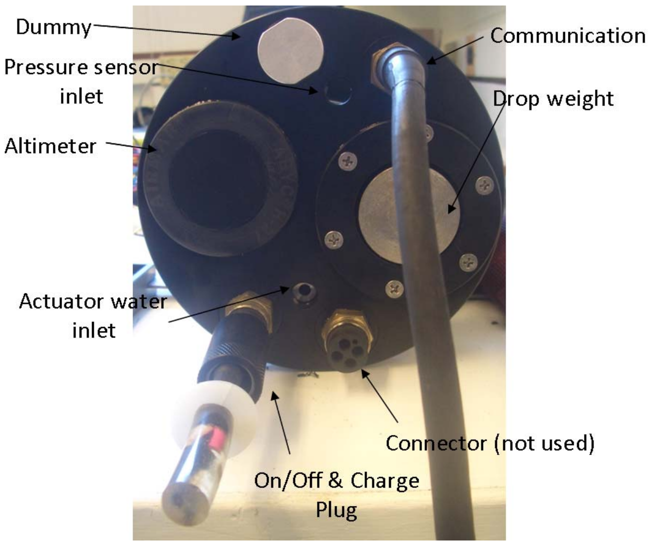


Fig. 4. Bottom view of the float. The end cap holds the pressure sensor port and altimeter, bulkheads for communications, power and future expansion of additional sensors, and the emergency drop weight mechanism.

enable an additional set more ideally Lagrangian behaviors such as isothermal, isobaric or isopycnal tracking. The actual ability and verification of the float to accomplish these tasks however will require considerably more testing than presented here and depend highly on the properties of the water column and the amount of mixing.

The main float electronics are powered by an OceanServer lithium ion rechargeable battery system with up to 300Wh capacity. This off the shelf system allows for easy discharge and charge monitoring, and regulated power outputs for the various electrical components. The battery capacity is continuously monitored by the main microcontroller.

The top endcap of the float is made from clear acrylic and contains ports for a vent screw and the Iridium antenna. The vent screw allows a vacuum to be pulled to seal the float and check for leaks. The clear endcap also allows viewing of an internal LCD battery monitor and vacuum pressure gauge. An independently powered emergency strobe is mounted in an internal recess in the endcap and visible from the top and side via edge lighting of a facet cut into the perimeter of the endcap.

The lower endcap also houses an emergency weight drop system to ensure the float is able to surface even in the event of a motor or controller failure with the piston fully retracted, figure 5. An simple disposable 1kg steel cylinder is held in an inverted cup by a high strength magnet. The magnet is fixed to the arm of a simple high torque model airplane servo. In normal operation the magnet holds the weight in the cup. To drop the weight the servo arm swings the magnet off the cup and the weight falls. This simple mechanism is easy to re-arm, has little chance of jamming and has no external latch or consumable burn wire that would require maintenance or replacement. Although the inverted cup can trap air bubbles at deployment the volume difference between the cup and weight is small. For a detailed discussion of air bubbles on floats and their time varying affect on buoyancy see [10].

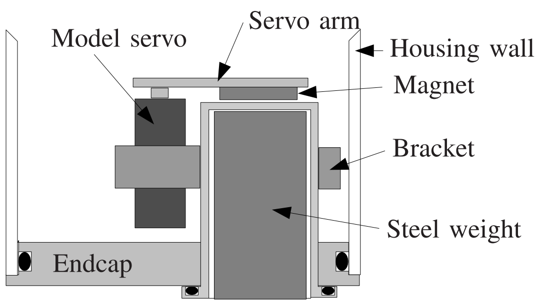


Fig. 5. Emergency drop weight mechanism. During normal operation the servo arm and magnet hold the steel weight. When triggered intentionally or by emergency the servo arm rotates (out of the page) dropping the weight.

B. Software and user interface

The core of the electronics and on-board computing is a Netburner $MOD5234$ microcontroller [17] that performs the depth control, data logging and the complete mission management. The Netburner is an easy to use microcontroller that runs “task” based code in a quasi-parallel manner. It directly supports Ethernet, serial and analog connections to sensors and the outside world. In our software implementation, “tasks” are run by a main scheduler and handle the basic operations of the float including; data logging, running the buoyancy control algorithm, reading and supervising a mission, and basic housekeeping for limits and emergency conditions. Any logged data is stored on a SD memory card and can be obtained via ftp or physically removing the card if the float is opened. Additionally, the Ethernet capability of the NetBurner is used to serve a status webpage that can be viewed when the Ethernet tether is connected. This easy web interface allows for fast debugging and testing of the float at the scene or remotely via the web.

The buoyancy control task uses measurements of both pressure depth and altitude above the bottom in a simple PID controller. The desired float position in the water column is specified by the current mission step. The controller computes an intermediate depth trajectory, shown in figures 8 and 9, using basic filtering to keep the desired depth changes within the dynamic capabilities of the float and avoid saturation and integrator windup. Additional steps are also included to account for intentional surfacings for Iridium communications, where all water is pumped out to achieve maximum buoyancy.

The mission planning is done using a mission scripting concept similar to that used in many AUVs [18], [19], [20]. An example mission script is shown in figure 6. The script contains an initial set of global variables that apply for the entire mission and become defaults for any subsequent commands. The remainder of the script is broken into time elapsed behaviors defined by a set of parameters. Once completed the mission script is transferred to the NetBurner by ftp and resides on the SD card. Figure 7 shows the 4 basic profiling behaviors which utilize both depth and altitude measurements. These profiles and simpler constant altitude or depth drifts can be set easily in the mission script.

The float software also supports emergency functionality. During a mission various signals are monitored, such as internal humidity to detect leaks, battery capacity and software error messages. A sufficient error condition can trigger an abort behavior via communication to an independently powered emergency board. This board is able to release the drop weight, figure 5, turn on the flashing strobe, and start Iridium calls with status messages for shore. This emergency board also receives a periodic alive pulse from the Netburner. Should the pulse stop the emergency board will drop the weight and force emergency calls.

III. Testing

To verify the performance of the float tests were performed in a controlled tank and Narragansett Bay (NB), RI. The initial tank tests were completed to verify the depth control performance of the float and the general time constants of its motions. Test results for depth performance in NB are shown in figure 8.

```
##########################
Section Global
  max_depth:          20   #m   maximum depth
  max_time:           51   #min total mission time
  min_altitude:       2    #m   minimum altitude
  min_depth:          1    #m   minimum profile depth
  min_battery:        20   #%   minimum battery abort
EndSection Global
##########################
Section Depth
  Time:               1    #min
  Depth:              2    #m   desired drift depth
EndSection Depth
##########################
Section Profile
  Time:               50   #min
  Max_Depth: 1        5    #m   bottom of profile
  Min_Depth:          3    #m   top of profile
  Down_Rate:          0.1  #m/s rate of sinking
  Up_Rate:            0.2  #m/s rate of assent
EndSection Profile
##########################
Section Home               #return to surface
  Comms_On:           1    #0|1  Iridium GPS comms
  Comms_Interval:     2    #min  Call frequency
EndSection Home
```

Fig. 6. An example mission for descending to 2 meters depth for 1 minute and then profiling for 50 minutes before surfacing to call home. The *Global* entries at the top are used for the basic health checking of the float during operation and take precedent over any other commands or adoptions.

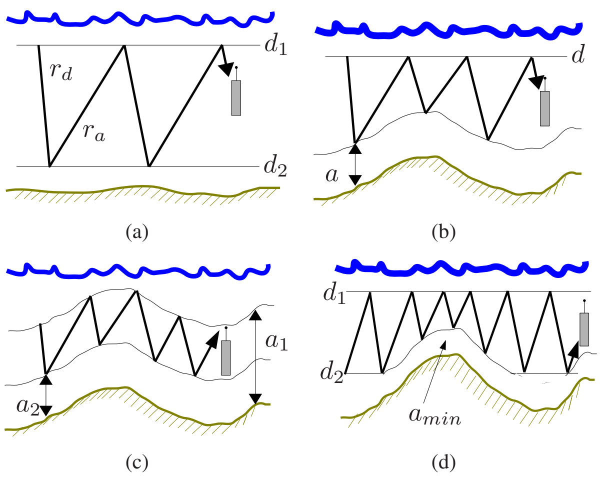


Fig. 7. Four basic profiling behaviors using combinations of depth and altitude limits. (**a**) Depth profiles with different controlled accent and descent rates. (**b**) Depth to altitude profiles. (**c**) Altitude limit profiles. (**d**) Depth profiles with a minimum altitude to avoid the bottom.

The profiling behavior of the float was tested in NB to verify the float is able to complete commanded vertical profiles at a controlled rate with acceptable overshoot on each end. Figure 9 show the result for profiles between to set depths.

Lastly, results are shown for a sample mission containing constant altitude drifts and periodic profiles to the surface, figure 10. This tests a likely data collection mission for the float where the profiles to the surface collect data and allow the float to call home and report its position to shore. It is important to note the float is able to correct for the total changing water depth and maintain a steady constant altitude.

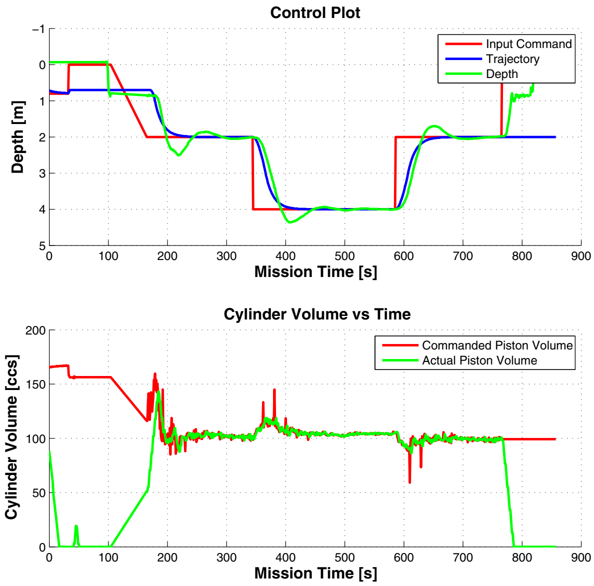


Fig. 8. Sample depth control mission of various steps. The float is able to step between depths and hold depths to millimeter bounds. Although some limit cycling exists at the steady values the amount is extremely small, tenths or less of cubic centimeters for the actuator.

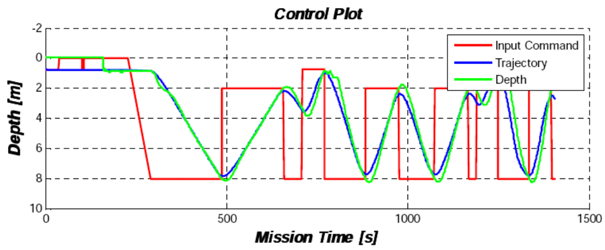
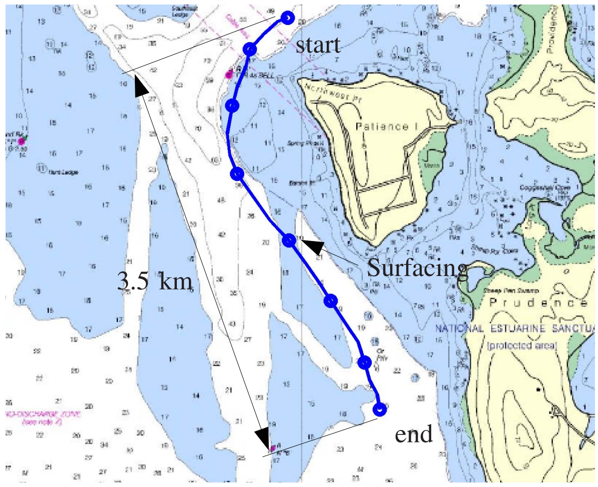
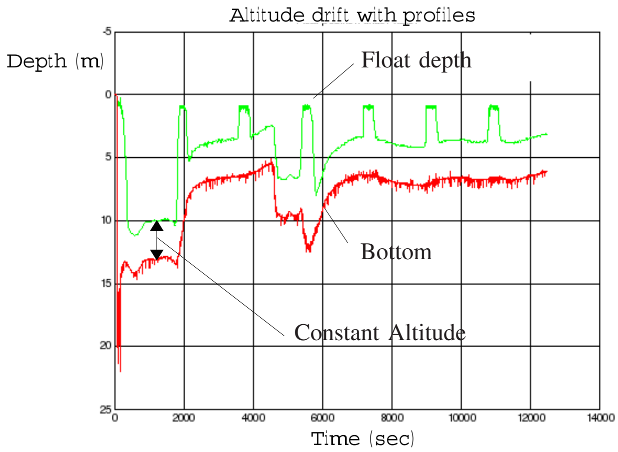


Fig. 9. Test of the profile behavior at $2.5\mathrm{m/min}$, $5\mathrm{m/min}$ and $10\mathrm{m/min}$ rates. Note the rate changes were not made to coincide with the end of a complete cycle.



(a) Drift track from trial



(b) Altitude following

Fig. 10. (**a**) Drift track from an initial test with the float deployed in a dynamic area of Narragansett Bay. Over 3 hours the float drifted 3.5 km in an outgoing tide. For the test, the position of the float was recorded every 10 minutes by noting the location of a small buoy tied to the float with a thin line. The surfacings were performed every 30 minutes. (**b**) Time plot of the float depth while following the bottom at a prescribed 3 meter constant altitude with periodic surfacings. Note the total water depth varied between 5 and 20 meters.

IV. Conclusions and Outlook

This paper has presented a design for a shallow water Lagrangian float which utilizes both pressure depth and altitude measurements to maintain a desired depth or depth trajectory in the water column. The design differs in several ways from the more typical open ocean floats and will provide a useful sensor platform in coastal waters. As this project continues, the next generation of the float will contain more optimized hardware to reduce power consumption and costs. The utility of such an instrument will be maximized by placing many of them in the field simultaneous and thus cost is an important consideration. Specific attention will also be paid to the tradeoffs between depth control performance, energy consumption and motor design for the buoyancy actuator. This relationship will be critical in planning missions in coastal waters with varying degrees of structure and mixing. The float has application for studying a wide range of problems in the coastal environment including basic water circulation and model verification, mixing and terrain influence on flow, phytoplankton distribution, and larval or contaminate dispersion.

V. Acknowledgements

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