Autonomous Vehicles for Remote Sample Collection in Difficult Conditions

Enabling Remote Sample Collection by Marine Biologists

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***Abstract*—Rapidly dropping costs and increasing capabilities of robotic systems are creating unprecedented opportunities for the world of scientific research. Remote sample collection in conditions that were once impossible due to expense, location, timing, or risk are now becoming a reality. Of particular interest in marine biological research is the aspect of removing additional stressors in the form of humans and equipment from whale monitoring. In a partnership between Olin College of Engineering and Ocean Alliance, a multirotor unmanned air vehicle (UAV) named *SnotBot* is being developed to enable marine biologists to collect observational data and biological samples from living whales in a less intrusive and more effective way. In Summer 2014 tests conducted in the Gulf of Mexico it was demonstrated that *SnotBot* may not be an irritant to whales of study with respect to the noise and downdraft generated by the UAV [1]. The results from those field tests are being used to apply for research permits to collect samples from real whales. Until formal authorization to operate over whales is granted, controlled testing at Olin College and in the Gloucester Harbor of Massachusetts Bay is being conducted to characterize the vehicles and develop autonomy. Beyond cetacean/whale research, the ability to collect physical samples in difficult or sensitive locations, as demonstrated by *SnotBot*, has far reaching applications in environmental monitoring, aerial surveying, and diagnosis of a transient events.**

***Keywords*—multirotor, remote-sampling, mission planning**

Fig. 1: *SnotBot* “White” is a modified *Aquacopter Project X Quadcopter Frame*. The chassis is completely waterproof, leaving only the motors, propellers, and waterproofed batteries exposed. Olin students modified it to include a landing structure, attachment points for a bottom-mounted camera, and robust internal electronics support structure. This is just one of several vehicles in the current fleet.

I. Introduction

Olin College of Engineering, founded in 1997 and home to 350 undergraduates in Needham, MA, has partnered with Ocean Alliance, a 501(c)3 organization that has been globally monitoring whales for the past 44 years. Together, we are co-developing a suite of robotic data collection assistants for marine biologists. These unmanned aerial vehicles (UAVs) called *SnotBots* will be used during field research voyages to monitor, track, diagnose, and study pods of whales in ways made possible only in the last few years.

This field research has the capacity to assess the general health of whales and ultimately the ocean, the state of which affects the entire planet [2]. Specific species of whale, such as the sperm whale, are of particular interest because they are apex predators. As such, they aggregate any existing toxins or chemicals in their environment. Samples of breath condensate, or blow, from whales contain material that can be analyzed for viruses, bacteria, stress hormones, DNA, and environmental toxins [3]. Research in this field has revealed critical data about the health of the whales and their ecosystem.

Current systems for collecting blow sample rely on the presence of a human researcher, manned boats, or gasoline-powered hobbyist vehicles, which usually disturb the whale and can be dangerous for the researcher. By designing a small, relatively unobtrusive intelligent robot to conduct these missions, researchers will be able to rapidly collect data from hundreds of meters away [4]. Additionally, *SnotBot* allows for sample collection in previously inaccessible locations during rare, short-duration events (e.g., when a whale is surfacing for breath). Before Olin College and Ocean Alliance can apply this technology to protected whales, we must demonstrate that there will be no adverse consequences when using the vehicle over a whale.

In order to simulate the anticipated interaction between

SnotBot and whale, a mechanical whale analogue, known as *SnotShot* and equipped with downwash and acoustic sensors, was developed for field tests. Both *SnotShot* and *SnotBot* were brought to the Gulf of Mexico in Summer 2014 for extensive field testing. This paper presents system details and the preliminary findings of this research journey, along with continued characterization efforts conducted by the research team.

II. System Development

SnotBot is a class of several open-source multirotor vehicles for conducting user-defined missions. A successful mission involves launch from a research vessel or ground station, navigation to predetermined waypoints or identification of waypoints (e.g., visually identifying a pod of whales or analogues), sample acquisition (e.g., waiting for surfacing of whale in the right position to catch the blow), and return to the launching platform. Our objectives for this year include design and implementation of a launch and recovery platform, modification of existing vehicles, deployment of a simple brain architecture, and an exploration of computer vision techniques for whale identification and vehicle navigation.

To assess the success of these objectives, an extensive system characterization testing protocol has been developed for controlled field testing. Anemometers, hydrophones, and video equipment are being used during these tests to collect data for later analysis.

A. Vehicle - SnotBot

The current *SnotBot* fleet consists of four quadcopters and four hexacopters. All vehicles are equipped with global positioning units, compasses, accelerometers, barometers, and magnetometers which allow real-time position tracking, useful for autonomy and data-logging purposes. All but one hexacopter use *PixHawk*, a commercial autopilot based on the open source *PX4* architecture, a highly customizable system for aircraft navigation and autonomy. The remaining hexacopter, shown in Fig 2, is a *DJI* platform that interfaces with a *Lightbridge* radio to stream HD video from a *GoPro Hero 3+* camera mounted on a gimbal.

Fig. 2: One of the hexacopters used primarily for overland testing and filming. This hexacopter uses a *DJI* system that interfaces with a *Lightbridge* radio to stream HD video.

The remaining hexacopters are a pair of recently acquired *HexH2Os* produced by *QuadH2O Multirotors*; one is shown in Fig 3. The *HexH2O* hexacopters extra arms provide increased lift as compared to quadcopters, and their bodies house modular electronics structures that allow easy component replacement. The *HexH2Os* have extra interior space for a gimbal and *GoPro Hero 3+* camera and have additional incorporated flotation attached to the shell.

Fig. 3: A representative picture of the new fleet hexacopters, which are a pair of recently acquired *HexH2Os* produced by *QuadH2O multirotors*. Picture courtesy of QuadH2O website, http://www.quadh2o.com.

Two of the four quadcopters, "White", shown in Fig 1, and "Grey", are *Aquacopter Project X Quadcopter Frames* with modifications designed and fabricated at Olin College. 3D-printed legs strapped onto the arms of these quadcopters serve as landing structures. The bottom of the quadcopter chassis also acts as the mounting area for a camera gimbal. Waterproof gimbal shields are currently being prototyped and developed. The electronics are mounted in a custom 3D-printed frame within the sealed plastic chassis, leaving the brushed DC motors, propellers, and waterproofed batteries exposed.

A third quadcoptor, an *Aquacopter BullFrog*, will be incorporated into the fleet in the near future. Like the *HexH2O*, this quadcopter is designed with filming, water landings, and customization in mind. The fourth quadcopter, an *IRIS+* from *3DR* is currently being characterized and added to the fleet as a software development platform.

Sample collection during field tests is accomplished by strapping surgical sponges to the bottom of the vehicle. *SnotBot* White successfully demonstrated sample collection by flying into simulated whale blow from *SnotShot* and acquiring viable samples during multiple field tests. The team is currently exploring an alternative to surgical sponges with an experimental weave of cloth from *Draper Knitting* that was designed for absorption and release of blood samples.

B. Whale Analogue - SnotShot

SnotShot is a whale analogue and sensor platform for field testing. The system, pictured in Fig 4, consists of a pressurized air reservoir, a water reservoir, a fast-acting valve, an ultrasonic proximity sensor, and a data logger connected to hydrophones and anemometers. The ultrasonic proximity sensor detects the presence and altitude of a multirotor vehicle up to 3 meters above the analogue. When a multirotor is detected, a trigger opens the valve and fires pressurized water through a 3D-printed blowhole. This blowhole is designed to launch artificial blow that mimics the spread and direction of a sperm whales breath.

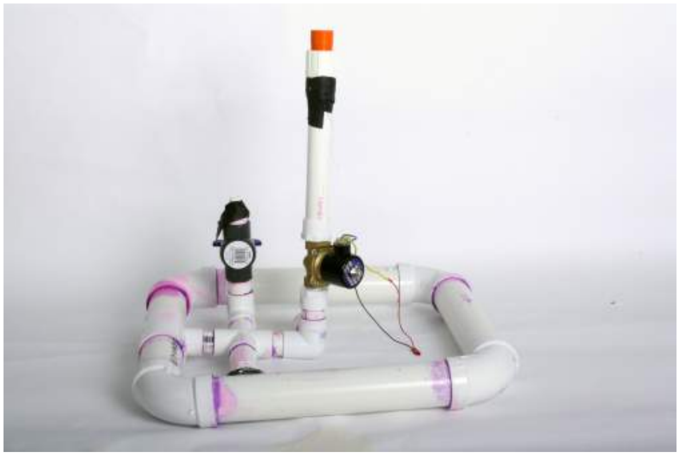

Fig. 4: *SnotShot*. When the pressurized air is released, the vertical reservoir of analogue snot is expelled from the3D-printed blowhole, pictured in orange.

C. Launch and Recovery Platform

The launch and recovery platform for *SnotBot* is being developed in preparation for future autonomous missions [1]. It is designed to be self-contained and mounted at a convenient location on the research vessel.

The launch and recovery platform, pictured in Fig 5, includes eight *Magswitch MagJig 60 keychains*, permanent on/off magnets spaced to interface with the landing structure. *Magswitch MagJig 60s* consist of two magnets. When both magnets are aligned, the poles also align generating a magnetic field; when one of the magnets is rotated 180 degrees relative to the other, the poles no longer align, effectively negating the fields [2]. *Magswitch MagJig 60s* were chosen because when in a steady state, they consume no power. A fiducial is also placed on the platform for the vision system to identify during landing procedure.

When the vehicle is airborne and preparing for landing, the *Magswitches* will be in the “on” configuration. When the vehicle touches the platform, the *Magswitches* will hold the vehicle with sufficient force to prevent accidental loss of the vehicle due to ship motion or wind. When the vehicle is preparing for take-off, the *Magswitches* will be in the “off” configuration.

D. Remote Control to Autonomy

SnotBot can be remotely controlled by a human pilot using a typical videogame-style joystick. To initiate, the human pilot

[1]Patent Pending

[2]“Technology,” http://magswitch.com.au/technology/

Fig. 5: A representative render produced in *SolidWorks* of the launch and recovery platform. *MagSwitches* will be used to catch the bottom of the landing structure of a *SnotBot* during landing, and can be turned off for launch.

launches the joystick control program at the base station, a central computer, on the research vessel, then engages the motors of the vehicle with the joystick.

This control program is written in Python and uses *ROScopter*, an open-source *ROS-MAVLink* library for the *PixHawk*, to send joystick commands to the multirotor.

ROS, Willow Garages Robot Operating System, is a programmatic method of layering behaviors and tasks for robotic systems. It is particularly useful for hardware-in-the-loop simulation, communications between multiple systems, and data handling. *MAVLink* is a communications protocol for aerial drones made popular by the *Ardupilot* and *PixHawk*. These were selected for this project based upon noted features, cost, availability of an open-source API, and standardization across multiple platforms.

Joystick control through *ROS* is a step towards developing more complex control commands independent of third party architectures. Sending our own commands through *ROS* allows us to develop algorithms and functionality that are much better suited to the particular needs of our intended human supervisors.

To date, we have developed and utilized several simple autonomy programs written in Python which control the height of a launch-and-land mission and send simple waypoint commands. In addition, we have adapted our *ROSCopter* library to handle the control of several multirotors at one time.

E. Mission Planning

Mission planning is being concurrently done with *MissionPlanner*, a publicly available user interface to *MAVLink* and *MAVROS* APIs created by Michael Oborne and supported by *3DRobotics*, and self-scripted programs as detailed in the previous section. The user interface of *MissionPlanner* allows for point-and-click waypoint selection on a geo-encoded map, user-defined control sequences for waypoints, and flight simulation capabilities. While *MissionPlanner* has some ability to parse self-designed programs, we have since branched into designing our own architecture that is tailored to the mission types that *SnotBot* will conduct. The ultimate goal of a self-designed mission and autonomy structure is to be able to interface a team-developed, base-station controlled brain written in Python, C, and C++ with an intuitive user interface such that non-robotic specialists can quickly and instinctively communicate missions to *SnotBot*.

In our initial development stages for the brain, a finite-state control loop is being built using a Python-ROS architecture that will consider sensor data and a JSON mission file uploaded by a human supervisor, assign a state to the vehicle, and issue commands to fulfill the mission safely and effectively. Future development for the controller will attempt to address issues brought out in field testing (e.g., communications errors and inclement weather), incorporate control loops for fine-tuned system response, and allow for changes to be made to the mission plan by a human human supervisor mid-flight. More sensing capabilities, smarter processing algorithms, and refined navigation methods will provide further development to our mission planner.

F. *Vision Development*

A key component of *SnotBot* is an onboard *GoPro Hero 3+* camera mounted on a stabilizing gimbal which communicates to the base station via the *Lightbridge* radio. The mission planner will run real-time vision processing algorithms to detect objects of interest (e.g., blowholes) and track targets designated by a human supervisor, allowing activities ranging from identifying pods of whales to isolating an individual from a group.

For our initial development, we integrated *ROS* with *OpenCV*, an open-source computer vision library, to process video streamed through the *Lightbridge* radio to track a QR code fiducial. *SnotBot* will be programmed to autonomously search for the QR code by detecting contours in each streamed frame and determining if there is a distinct pattern of black and white squares. Once the fiducial is detected, the multirotor will center itself directly over the code for a certain amount of time, in order to simulate the collection of blow or preparation for landing.

Contour detection, while efficient at tracking QR codes, is presumed to be sub-optimal for detecting whales on the surface of the ocean. Better options available through the *OpenCV* library, such as HSV object tracking or machine learning, could be implemented instead. With HSV object tracking, it is possible to differentiate between marine animals and the surrounding water based on color differences [5]. With machine learning it is possible to use pre-existing video of whales as our training data, so that *SnotBot* will only track objects that look like blowholes.

Vision will also serve an important role in controlling the landing on the launch and recovery platform. To date we have created the foundational code for identifying and tracking a moving target. On the platform is a fiducial which the multirotor can identify at varying altitudes and orientations, providing relative positional information that enables *SnotBot* to land autonomously. Moving forward, controlled field testing will aid in the development of a robust vision system that can function in varying weather and lighting conditions more typical of the open waters.

III. SYSTEM CHARACTERIZATION

In order to consistently evaluate the robustness of the fleet vehicle firmware and software, we have developed a quantitative and qualitative characterization protocol. These measure vision accuracy, navigation accuracy, and flight accuracy, in addition to acoustic and downwash measurements. As development of the fleet continues, these will become more relevant in day-to-day testing operations.

A. *Characterization Protocol*

For the vision systems, we need to determine whether we can precisely identify the location of a whale to most effectively collect a sample. A tiered protocol has been designed which escalates from remote-control ground tests to autonomous water tests. At the first tier, a fiducial is placed on the ground and a human operator guides the vehicle to an altitude of approximately 40 feet. The human operator traces a square path with the multirotor as the gimbal tracks the fiducial. The second tier begins an active autonomy test in which the fiducial is placed on a moving target for the vehicle to follow. In the third and final tier, both of these tests will be conducted over water to determine the impact of glare on the vision system. For all tiers, data of interest include line of sight accuracy, ambient environmental conditions, and system time delay.

To determine the accuracy of the navigation system, a grid of waypoints can be programmed as a mission file into the base-station. This mission plan will be recreated physically in a field using orange cones and altitude recorders at each waypoint. Theses recorders are only triggered if the vehicle is hovering directly above the sensor). Using the GPS data sent from the multirotor to the base station and the data collected at each waypoint, we can determine the GPS drift of the system. This may be useful in informing a controls compensation algorithm.

Flight characteristics include noise and downwash. Using hydrophones in a closed environment - a pool located on Olin Colleges campus - the noise of the motors and propellers can be measured at varying heights above the surface of the water by sending thrust commands to the vehicle as it is manually held above the pool. For downwash tests, the multirotor is held manually at varying heights above two anemometers, one placed in line with the propellers and one orthogonal to the propellers, and given an altitude hold command.

The flight characterization methods are of particular interest to whether or not *SnotBot* will be noticed by a whale. To date, this test has been run to compare two of our fleet vehicles - an *IRIS+* quadcopter and a *DJI Flame Wheel F550 hexacopter*.

B. *Sample of Results*

Controlled tests of two vehicles in the fleet, a *DJI* hexacopter and an *IRIS+* quadcopter, have been completed up to the date of this paper. The results indicate that both of these fleet members could have limited, if any, impact on a whale. Seen in

Fig 6, acoustic tests show that within a controlled environment, while the signature of both multirotors is detectable under the water, there are no particularly concerning peaks that are significantly louder than even ambient splashing. Indeed, the sound detectable in a still pool is within a range of 20dB to inaudible. This is an extremely low level, especially considering that whale research provided by Ocean Alliance and independent parties indicates that whales need sounds above 140dB before being considered audible [6] [7].

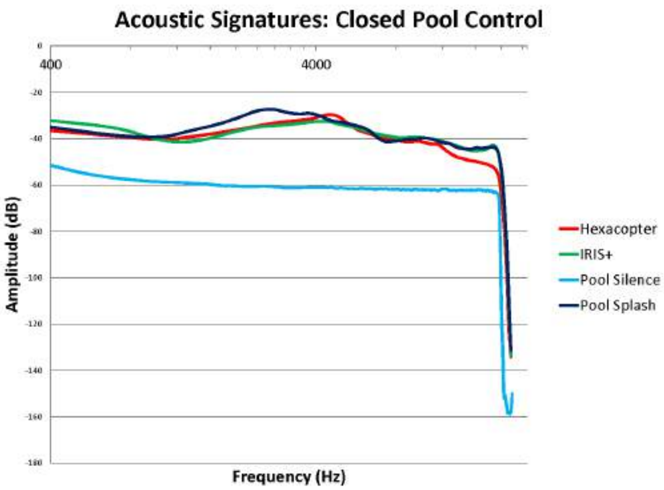

Fig. 6: Measured sound intensities in a silent pool of an *IRIS+* and *DJI* hexacopter. Results indicate that some noise is detectable under the water, but the noise produced was no more disruptive than ambient splashing. Vehicle height over the water was approximately 1 foot.

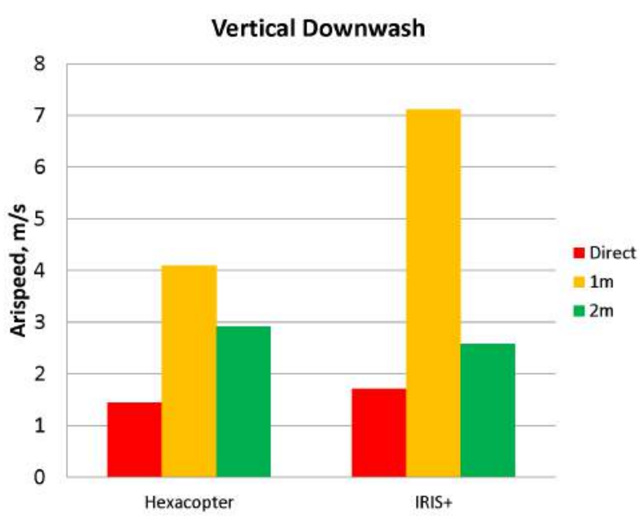

Fig. 7: The vertical downwash measured of both vehicles at varying heights. The small downwash recorded for direct measurements is reflective of the stagnant bubble that sits under the vehicle.

Further, the anemometer data, displayed in Figs 7 and 8, indicates that at low-altitudes, the multirotors may produce air velocities as fast as a typical ocean breeze (approximately 5 meters per second) [8]. Given that the modus operandi for

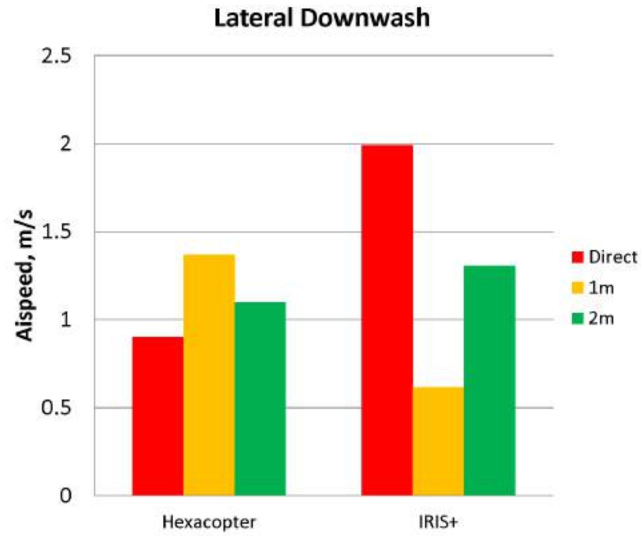

Fig. 8: The lateral downwash measured of both vehicles at varying heights.

the vehicle will typically be of about 3 meters or higher, the downwash produced by the multirotors should be negligible to the whale of interest.

IV. Field Tests

A. Experimental Methods

Before *SnotBot* can be deployed with whales, it must be determined whether or how the multirotor may affect a whale as its hovers over the animal. While controlled characterization is important, field testing is of particular interest for data collection in order to have a sense of the true impacts the vehicle might make when deployed in nature. A team from Olin College traveled to the Gulf of Mexico in the Summer of 2014 with Ocean Alliance to participate in Operation Toxic Gulf, a mission dedicated to understanding the chronic effects of the Deepwater Horizon disaster and the unprecedented use of dispersant on Gulf wildlife. During the course of this trip, *SnotShot* was deployed into the open ocean and a human pilot flew a *SnotBot* over the whale analogue while sensors were logging data. Multiple open-water flying tests were also conducted over the course of the journey.

The hydrophones, located one and three meters below the surface of the water, measured ambient ocean noise and the noise of a multirotor flying overhead. Hydrophone locations were chosen to match the points where the auditory bulb for small and large whales would be located when surfacing. The anemometers measured the speed of the downwash from the propellers. An image, captured from another multirotor in the fleet during testing is shown in Fig 9.

B. Preliminary Results

Upon return from the Gulf of Mexico, the anemometer and hydrophone data were processed and preliminary analysis conducted. The anemometer data did not show any conclusive evidence about the downdraft of the vehicle in relation to the ambient winds. Over the course of the testing periods, an hour

Fig. 9: Image from one of the fleet of *SnotBots* watching another *SnotBot* approach *SnotShot*, the whale surrogate. This was taken during field testing in the Gulf of Mexico Summer 2014.

of ambient audio was collected. Approximately 20 minutes of recorded audio consists of active *SnotBot* testing. Post-processing results of the data indicate that *SnotBot* noise, in comparison with normal ambient ocean noise, appeared louder in the 14 kHz frequency band. However, the sound intensity in this band was well within ambient ocean noise levels, as can be seen in Fig 10.

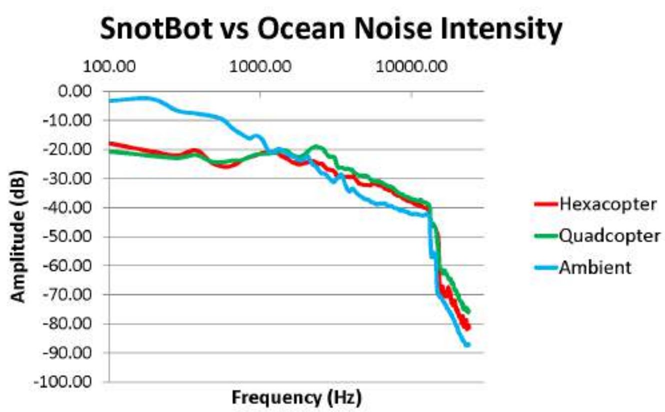

Fig. 10: For both the hexacopter and quadcopter models, the sound intensity in the 14kHz frequency range is higher than ambient sound. Given the overall intensity level and frequency range of note, it is determined that when compared to motor boats and similar testing vessels, *SnotBot* is more discrete.

Research on whale hearing conducted over the past decade indicates that whales respond to sounds 140dB and louder, with ranges of sensitivity under 10kHz and above 100kHz. Little is known about the stress response of whales to the quiet sounds observed in the testing conducted in the Gulf. Information collected by Ocean Alliance indicates that, of sperm, blue, humpback, dolphin, and beaked whales, only sperm whales have a hearing range which could potentially detect the frequency of noise from the propellers on the multicopter, though the likelihood of being able to detect the sound at such a quiet volume is very low. Compared with traditional methods involving small watercraft with gasoline-powered engines [9], we believe that *SnotBot* could be the most discreet method of collecting samples from a whale.

V. Conclusions

The study of whales informs us about an entire ecosystem's health. Based on preliminary findings and field testing, we believe that *SnotBot* provides benign techniques for whale sample collection during ocean research trips. *SnotBot* will allow for more frequent data sampling with little-to-no induced stress to the target whale populations.With the rapid improvements of commercial multirotor technology, combined with an active open source community working on improved autopilot software, we believe *SnotBot* has the potential to be a cheap, human supervisor- and whale-friendly research tool accessible to marine biologists in the near future.

VI. Future Work

The 2014-15 academic year has been devoted to redesign and further development of the *SnotBot* and related systems, with a particular focus on integrating the launch and recovery platform. As further autonomy is developed during late spring 2015, these systems will be tested in Gloucester Harbor and additional data will be collected regarding system-whale experience. Data collected will also inform iteration development, particularly focused on the usability of APIs, autonomy efficiency, and robust chassis design. In the summer of 2015, we hope to collect blow samples from three different species of whales, experimenting with different user interfaces, and rigorously testing our equipment.

Acknowledgment

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