Towards Autonomous Aerial Water Sampling

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***Abstract*— Obtaining spatially separated, high-frequency water samples from rivers and lakes is critical to enhance scientists' understanding and effective management of our fresh water resources. This paper explores a system to take water samples autonomously from a UAV. The aerial water sampler has the potential to vastly increase the speed at which scientists obtain water samples, ranging over larger areas, while reducing cost and effort. We augment a commercial hexacopter with a water sampling system that includes: 1) a mechanism to capture three 20ml samples per mission; 2) a family of sensors to provide safe navigation and approximation to the water surface; and 3) a set of distributed software components that integrate and analyze the sensor data, control the vehicle, and drive the sampling mechanism. In this paper we validate the system in the lab, characterize key sensors, and present preliminary results of outdoor experiments. These experiments show that despite the challenges associated with flying precisely over water, it is possible to quickly obtain water samples with a UAV.**

I. INTRODUCTION

Water quality varies due to the spatial distribution of water transport pathways and contaminant source areas. Characterizing this large-scale variability remains a critical bottleneck that inhibits understanding of transport processes and the development of effective management plans to address water quality issues. In the US, it is estimated that human-induced degradation of freshwater sources annually costs over $2.2 billion, but the full extent of the cost is poorly known due to insufficient data [1]. World-wide, water borne diseases cause the death of 1.5 million under-five children every year [2].

Current water sampling techniques are often based on grab sampling (e.g. dipping a bottle off the side of a kayak) [3], statically deployed collection systems [4], or using mobile sensors affixed to Autonomous Surface Vehicles (ASVs) [5] and Autonomous Underwater Vehicles (AUVs) [6]. Most autonomous systems are used on large, open water features such as seas, large lakes and rivers, and sample for long duration, in deep or distant places, with high quality. All of these methods are relatively slow, spatially restricted, costly, or difficult to deploy; none sample quickly at multiple locations while overcoming barriers, such as dams or land.

In this paper, we start tackling these limitations through the prototyping of a UAV-based water sampling system with a focus on enabling *safe and reliable* in-the-field water sampling. Fig. 1 shows the prototype system collecting a water sample. We designed the system based on input from our limnologist collaborators who identified $20ml$ as a baseline quantity for chemical analysis, and required that the system be carried and deployed by a single person to collect multiple samples within kilometer ranges.

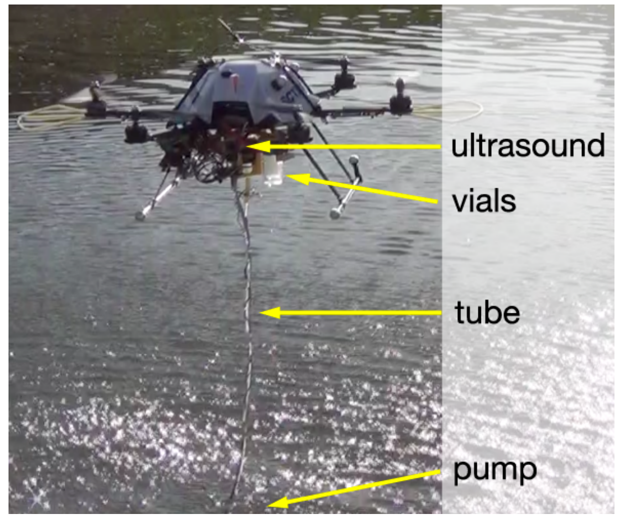

Fig. 1: UAV-Based Water Sampling.

Obtaining water samples from a UAV, however, poses a number of challenges that must be addressed before these systems can be deployed in the wild. The contributions of this work include: 1) developing a UAV-based system that autonomously obtains three $20ml$ water samples per flight; 2) integrating and characterizing sensors on the UAV to enable reliable, low-altitude flight ($< 1m$) over water; and 3) testing the system both indoors in a motion-capture room as well as in the field at a human-made waterway. We also identify a number of outstanding challenges to be addressed in future work, such as determining the impact of waves, winds, and flowing water on altitude control.

II. RELATED WORK

Existing efforts relate to this work in one of two ways: either an autonomous vehicle is used to take samples in aquatic environments or a UAV is controlled at low-altitude. We treat first the former and then the latter.

Autonomous vehicles used in water sampling are either Autonomous Surface Vehicles (ASVs) or Autonomous Underwater Vehicles (AUVs), both deployed in large water features such as oceans or large lakes. For example, Dunbabin *et al.*'s [5] Lake Wivenhoe ASV is capable of navigating throughout complex inland waterways and measuring a range of water quality properties and greenhouse gas emissions.

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Underwater, Cruz *et al.*'s [6] [7] MARES AUV dives up to $100m$ deep and monitor pollution, collect data, capture video, or follow the seabed. Other efforts such as Rahimi *et al.*'s [8] NIMS system explore semi-mobile sensor networks providing adaptive sampling. These vehicles and systems sample for long duration, in deep or distant places, with high quality. Accordingly, they are expensive and time-consuming. In contrast, we designed our system for short missions, nearby, carried and deployed by an individual, capable of flying over impediments, and for reasonable cost. Further, *in situ* sampling cannot yet measure all desired water properties, identified by Erickson *et al.* [4], such as the presence of suspended solids, pathogens, and heavy metals.

Other UAV control systems related to our efforts include the approach to system states. Merz *et al.* [9] show techniques for low-altitude flight in rural areas, whereas low-altitude over water is our goal and the scope of our work does not include obstacle avoidance. Their system states, like ours, contain events indicating an unsafe circumstance, and transition to a state seeking safe recovery.

Other recent efforts for UAV height estimate include miniature radar altimeters and optical flow altitude estimation as summarized by Kendoul [10]. The lightest current radar altimeters are still $375g$, heavy for a micro UAV, and optical methods are easily perturbed by ambient light, so instead we chose ultrasonic rangers. Further, miniature radar altimeters measure up to at least $700m$, far above the requirements of our system. We are concerned with accuracy within the last few critical meters above water.

Our system flies with a small dangling pump. Although Sreenath *et al.* [11] explore the flight dynamics of cable-suspended loads, our system avoids this by hanging a small mass, which incurs small forces relative to those generated by our UAV.

Our work most resembles the low-altitude autonomous UAV presented by Göktoğan *et al.*[12], wherein the authors surveil and spray aquatic weeds at low altitude using a RUAV ("rotary UAV"). This RUAV measures altitude with a laser altimeter, and like our system, requires a human backup pilot. Our work similarly does not address global planning and requires a human expert to decide where to perform tasks (weed experts in Göktoğan's case and lake experts in ours). Our work differs from this in that we use ultrasonic with pressure for altitude and retrieve a liquid rather than depositing it.

III. Applications In Environmental Monitoring

Presently, limnologists and hydro-chemists require water samples for lab analysis. They measure chemical properties of surface water, including dissolved phosphorus, orthophosphorous, nitrate/nitrite, nitrogen, and ammonia, as well as biological properties, such as the presence of toxic microcystins. Other useful properties can be measured *in situ*, but require a literal boatload of equipment, used to measure temperature, conductivity, pH, dissolved oxygen, light, turbidity, and Secchi transparency. All of these field measurements, along with lab analysis, together present much of the canonical data through which surface water phenomenon are understood [13]. By facilitating data collection, lightweight UAVs, together with our collaborators, will improve, if not "revolutionize" spatial ecology [14]. We see applications of UAV-based water sampling in two areas: 1) increasing the ease of capturing routine small samples from disconnected water features; and 2) improving the quality of event-based datasets.

Fig. 2: Sandpit Lakes - Fremont, Nebraska, USA

For example, our collaborators study the Fremont Sandpit lakes (see Fig. 2), near Fremont, Nebraska, USA. Each numbered lake is disconnected, chemically-distinct, and must be sampled separately. Currently, a team of three scientists tow a boat to the lake by truck, launch the boat, navigate to the sample location, collect samples and take measurements, return to dock, get the truck, put the boat back on the trailer, and drive to the next lake. Each of 10-15 lakes are sampled in this manner over a long 10-15 hour day. However, a small UAV, with 3 $20ml$ vials and 1 km range, could acquire 10-15 water samples on these lakes in 2 hours, allowing the water scientist options of greater spatial or temporal resolution in these routine samples. In addition to routine sampling, we forsee the ability of water-sampling UAVs to create ad hoc datasets in response to environmental events, capturing data with unprecedented spatiotemporal resolution.

The system described in this paper alone does not create a synoptic view of this ecosystem, but rather begins to address the challenges in automating this process, and could be augmented with additional sensors and / or vehicles.

IV. System Overview

The system is constructed using component-based design, emphasizing vehicle safety while flying over water. We used an iterative design approach with rapid prototyping in software, electronics, and mechanical systems. Using a commercial hexrotor UAV allows us to assume stable hover and decreases the risk of system failure due to errors in bootstrapping a UAV. Components in our design included a commercial UAV, a 3-D printed assembly to join vials and servos, the Robot Operating System (ROS) [15] for integrating onboard and off-board subsystems, and off-the-shelf sensors, micro-controllers, servos, and pump. The remainder

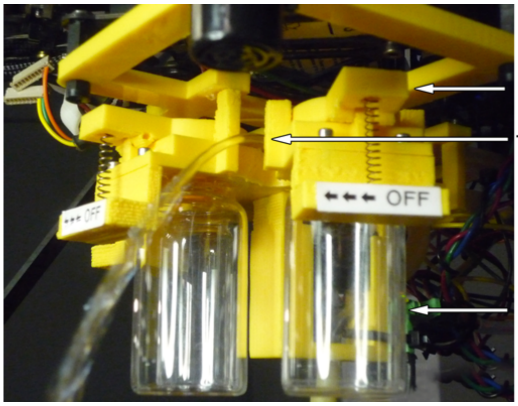

Fig. 3: Pumping in Flush Position

of this section discusses how these components are used to accomplish the mission while keeping the UAV safe.

To stay safe and dry, we used three layers of redundancy: 1) duplicate ultrasonic sensors; 2) ultrasonic and pressure-based height estimate; and 3) configuring the UAV to default to a pressure-based hover in case of catastrophic failure of radio connection or off-board control.

The approach to control is to use a system built on top of ROS for off-board control from a portable computer. The system is responsible for mission planning, generating UAV control inputs, collecting sensor data for height estimation, sending control signals to the pump and servo, and data logging.

We chose ultrasonic sensors instead of other means (like laser or radar altimeters) because ultrasonics are less expensive, lighter, less sensitive to ambient lighting, and unaffected by the translucence of the water. We added two downward-facing ultrasonic rangers to increase the likelihood that at least one always has an unobstructed path to the water.

Our approach to sampling is to use the same tube for every sample, and therefore we use a 'flushing' or purge phase between samples wherein water is pumped up through the tubing and ejected overboard (see Fig. 3). The duration of the flushing phase is configurable, defaulting to $6s$, the same duration required to fill a $20ml$ vial, although a rigorous exploration of managing cross-contamination with flushing is planned for future work.

As an additional layer of safety, we assume a human backup pilot, and in case the remote control system fails (power failure) or the radio control link is severed, control instantly and automatically reverts to a pressure-sensor-based user control, which tries to maintain altitude and stability until the pilot intervenes.

V. Technical Approach

Through discussions with our hydrologist partners we derived a set of requirements for the aerial water sampler. First, it must be able to capture at least three $20ml$ water samples over a set of predefined locations distributed within a radius of 1 km. Second, it must be light and small enough to be carried by a single scientist, and perform water sampling autonomously once the sampling locations are identified. Third, it must do so reliably and safely to reduce risk and cost since these are the primary barriers for adoption.

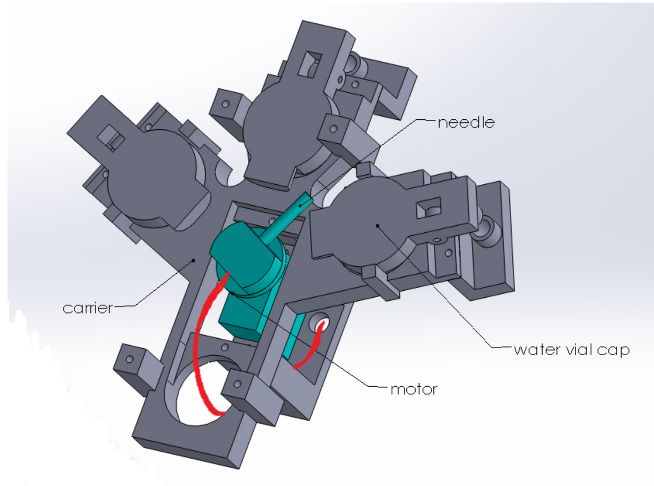

Fig. 4: Sampling Mechanism

We now describe how we address these requirements through: 1) the mechanical design, including the UAV as well as the sampling mechanism; 2) the sensors with which the UAV is augmented; 3) the software system, including a brief discussion of the safety logic used to ensure the vehicle stays out of the water; and 4) the altitude estimate formed with a Kalman Filter.

A. Mechanical Design

The water sampler is built onto an Ascending Technologies Firefly [16], a hexrotor with a maximum payload of $550g$. The total flight time is 15 to 20 minutes. The Firefly comes equipped with GPS, 3-axis accelerometers, 3-axis gyroscopes, compass and an air pressure sensor (altimeter). This UAV communicates with a human backup pilot using a radio link, and has two $2.4GHz$ 802.15.4 radios for remote autonomous control and sensor feedback.

The water sampling mechanism consists of three spring-lidded chambers. The chambers are constructed so that a servo-rotated 'needle' lifts the lid and directs the water flow into one of three $20ml$ glass vials (see Fig. 4). Once the needle rotates away from the vial, it seals closed. The servo can also select an intermediate position to enable flushing of the needle and tubing between samples (see Fig. 3). The needle is connected to a $1.05m$ plastic tube hanging below the UAV with a micro submersible water pump [17] attached at the end of the tube. The tube is mounted below the center of mass of the unloaded vehicle, to minimize changes in flight dynamics while pumping. A break-away mechanism allows the pump and tube mechanism to release if subjected to a sufficient force, as might happen if the pump becomes entangled in the environment, and the UAV thrusts away from it.

B. Sensors

The Firefly includes an onboard pressure sensor. To improve height estimation, we augment the UAV with ultrasonic

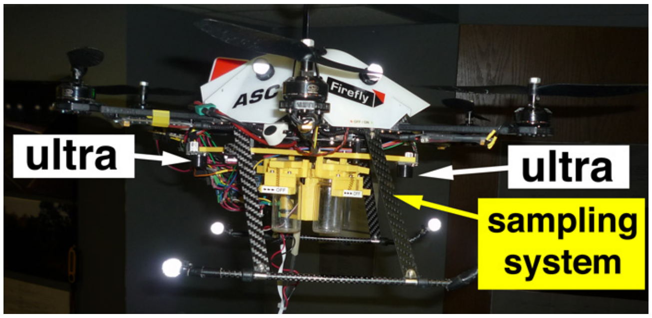

Fig. 5: Sampling System From Side

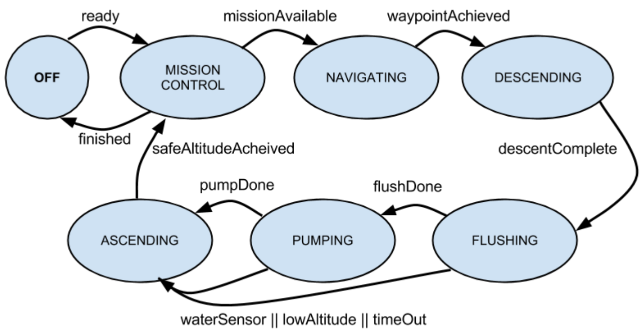

Fig. 6: Sampling States

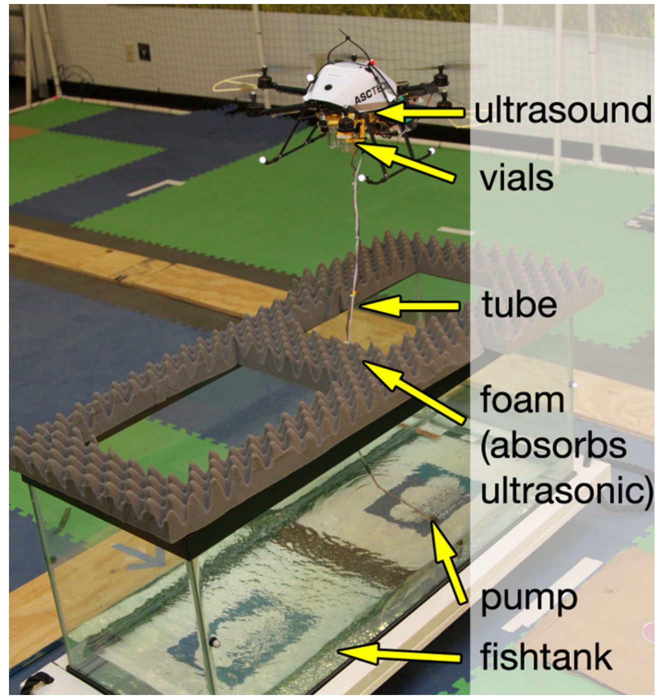

Fig. 7: Fishtank: Testbed for Indoor Water Sampling

rangers and water conductivity sensors. We use two ultrasonic rangers [18] flanking the sampling mechanism $10cm$ from the center and pointing straight down, as shown in Fig. 5. This configuration increases the chance of having an unobstructed path to the water's surface, which might otherwise be blocked by the tube and pump. Each ultrasonic ranger samples at $10hz$ and we offset their sample time by $50ms$ to prevent interference. This also increases the rate that altitude information is acquired to $20hz$. We chose this particular rangefinder because the manufacturer recommends it for UAV applications, specifically it's resilience to motor noise and reliability between $0.2m$ and $4m$, our critical altitude.

The pump must be primed prior to operation. To ensure that the pump is submerged and primed before turning it on, we add a conductivity sensor at the pump that can detect the presence of water. Similar sensors on the sample tube at $30cm$ and $70cm$ above the pump help to detect when the UAV is safe to operate or too close to the water, triggering an increase in altitude. An onboard controller turns on the pump only when the water sensor detects that it's been in water for more than $400ms$, a delay sufficient to ensure that water floods and primes the pump.

C. Software

The software system is comprised of two sub-systems: 1) off-board code built on top of ROS, which handles low-level communication with the UAV, mission control, navigation, and high-level sampling tasks; and 2) on-board code rapidly prototyped and deployed on an Arduino micro controller mounted on the UAV that manages the 'needle' servo, regulates the water pump, reads ultrasonic and water sensor data, and broadcasts the water-sampling sub-system's state. Both sub-systems incorporate predicates that detect unsafe water sampling or navigating conditions based on the sensor readings, and restart a mission. In total, the system includes about 5K lines of C and C++ code.

The flow of water sampling activities is shown in Fig. 6. The software coordinates these activities through: 1) waypoints, which are compared to the measured location of the UAV, so that the UAV arrives at the desired sample location and descends to the target height; 2) timers, which track how long the pump has actually been pumping and infer that the tube has been sufficiently flushed or that the vial is full; and 3) safety predicates on sensor values which ensure the sampling altitude is safe. If the safety constraints are violated, the UAV retreats to a safe altitude and the mission continues.

D. Kalman Filter Based Altitude Estimation

Since the on-board pressure sensor is not sufficiently accurate, we form an altitude estimate based on a Kalman Filter that takes the two ultrasonic range readings and the pressure sensor as input. Noisy readings from an individual ultrasonic sensor are rejected if the variance over the past second is greater than $0.08m^2$ or the readings are too far from the current filtered estimate. If both ultrasonic readings are good, then they are averaged before input into the Kalman filter.

VI. Sensor Characterization

In this section we summarize the empirical characterization of the following water sampling subsystems: pump, conductivity, pressure sensor, and ultrasonic range sensors.

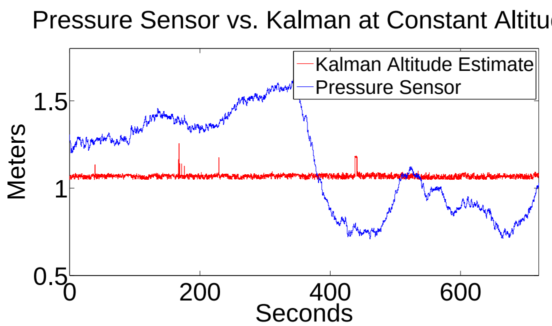

Fig. 8: Pressure Sensor Outside at Fixed Altitude

A. Pump Characterization

The micropump lifts water at $230\frac{ml}{min}$ to a height of 1 meter and requires 0.3 Amps at $4.2V$. At $1m$, it takes $1-2s$ for the flow to reach the top of the tube, and then the pump fills a $20ml$ vial in $5-6s$. The pump flow rate is unreliable for tube lengths longer than $1m$.

B. Water Conductivity Sensors

We constructed water sensors by measuring the conductivity of representative water samples, and designing a circuit based on this parameter. We have observed that the sensor reacts in less than $0.5s$ when placed in water, and we placed the wires on opposite sides of the sampling tube so that one droplet of water would be less likely to linger and give a false reading. Fig. 11 and 12, show how the water sensors are engaged during sampling, which both monitor altitude safety and regulate whether the pump is on.

C. Pressure Sensor

The pressure sensor data is useful because it is reliable for short periods of time if the ultrasonic data is noisy, and we incorporate it into the Kalman height estimate. However, the pressure sensor is susceptible to noise from gusts of wind and to drift from temperature or atmospheric pressure changes. To characterize the pressure sensor we placed the UAV outside at a fixed altitude, and recorded the pressure sensor and Kalman altitude estimate for 12 minutes. Average wind speed during this test was $1.3ms^{-1}$, measured every minute with a hand-held anemometer. As shown in Fig. 8, the pressure sensor drifts more than $90cm$ in 100 seconds, which demonstrates that the pressure sensor data is subject to drift over time as the ambient pressure of the environment changes, and disqualifies it for low-altitude reliability.

D. Ultrasonic Range Finder

We characterized the ultrasonic rangefinders over water by conducting indoor flight tests with ground truth from a Vicon motion capture system [19]. We tested these to determine their performance while flying and over water. The results are show in Fig. 9-10. The rectangles in the figures highlight the duration during which the UAV was over water. The ultrasonic ranger is sampled at $20hz$, and the datasheet claims an accuracy of $\pm 1cm$. The data was gathered during autonomous flight, flying the UAV to $2m$ above the fish tank, then descending by half-meter increments to $1m$, before returning to $2m$ and leaving the over water area. We placed acoustic foam over the fish tank (Fig. 7) to absorb the ultrasound readings so that the edge of the tank is not detected.

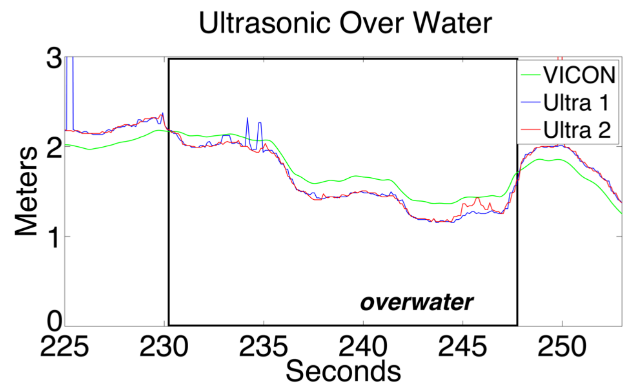

Fig. 9: Vicon and Ultrasounds

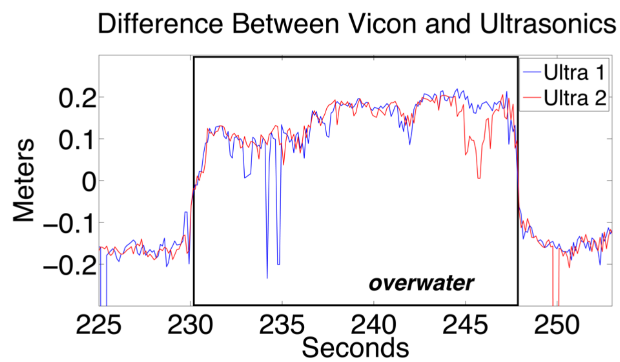

Fig. 10: Difference between Vicon and Ultrasounds.

As seen in Fig. 10, the difference between the ground truth and ultrasonic is greatest while the UAV climbs or descends, which is caused by the latency of the ultrasonic compared to Vicon. Additionally, when the UAV is over water there is a larger offset from Vicon due to the height of the water in the tank. There are also sporadic large spikes when the ultrasound gets an invalid reading and occasional smaller values caused by detection of the pump. In practice, these variations are rectified by the Kalman filter. These experiments show that the ultrasound performs well over water, although having more than one sensor is important to filter sporadic noisy readings.

VII. Experiments

Through the following experiments we seek to explore the effectiveness of the water sampling system. In particular, we are interested in investigating the precision of the ultrasonic rangers and pressure sensor when operating over water. As part of this section, we also discuss our preliminary outdoor experiments that illustrate the potential of the system to reliably serve environmental scientists.

A. Kalman Altitude Estimate Effectiveness

Fig. 11 shows how the Kalman altitude estimate tracks closely to the Vicon “ground truth”, both during approach and during indoor sampling. Notice during the ‘Approach’

ALTITUDE	Trials	Samples	Full	$> \frac{1}{2}$	$< \frac{1}{2}$	%
VICON	15	45	41	3	1	91.1
ULTRASONIC	15	45	40	3	2	88.9
TOTAL INDOOR	30	90	81	6	3	90.0
OUTDOOR	13	39	27	4	8	69.2
GRAND TOTAL	43	129	108	10	11	83.7

TABLE I: Sampling Success Rate

portion the altitude estimate continues accurately in spite of Ultra 1's noisy data spikes. Also during sampling, note how the height estimate closely follows Vicon, with an offset caused by the height of the water in the tank. This figure demonstrations that the Kalman altitude estimate is a robust, responsive, and effective.

B. *Water Sampling Effectiveness - Indoor*

We tested the water sampling system in a controlled indoor environment. We wrote an autonomous mission that launches the UAV to $2m$, flies over the fish tank, descends to the sampling height where the pump is submerged, takes a sample, and then ascends back to $2m$. Each test consisted of three samples, and afterward the water sample vials were checked. Any amount less than the top of the 'neck' of the sample vial was recorded as less than full. We completed a total of 30 trials. Each trial took 4-5 minutes flying, with an additional 5-10 minutes to set up the system, empty the vials, and periodically change batteries.

Table I summarizes the results. Overall, from the 90 consecutive collected samples indoors (30 trials with 3 samples each), 81 were full (90% success). To better understand the relation between the success rate and the use of our ultrasound and pressure altitude controller, half of the samples were collected using the altitude reported by the Vicon motion capture system. The first and second rows of Table I show that the success rate is nearly the same for both Vicon and ultrasonic altitude, which indicates that ultrasonic rangers are suitable for height estimation over water.

Of the indoor sample failures, six of nine were over half-full. Failures were caused by the pump landing outside the fish tank (we used a narrow fish tank to prevent the UAV from falling into the water during the system development) or the pump failing to self-prime.

C. *Indoor and Outdoor Height Control*

We performed preliminary outdoor experiments to check the viability of the water sampler in unstructured environments, and to evaluate the altitude estimation. The outdoor location was a man-made waterway along Antelope Creek in Lincoln, Nebraska, USA. The water at this location is less than $2m$ deep. For these preliminary tests we chose a calm day with wind speeds measured at less than $0.27ms^{-1}$ with a hand-held anemometer. Fig. 1 depicts our system successfully operating in this context.

To compare the indoors versus outdoors experiments, we recorded the ultrasonic, pressure sensor, and Kalman-filtered height estimate, as shown in Fig. 11 and 12. The highlighted regions show the UAV while it 'approaches' the sample destination and the critical 'sample' stage during which the UAV must descend and maintain altitude to pump water.

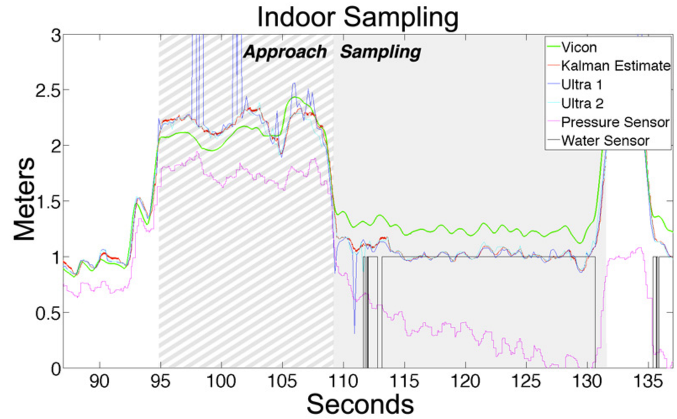

Fig. 11: Indoor Sampling

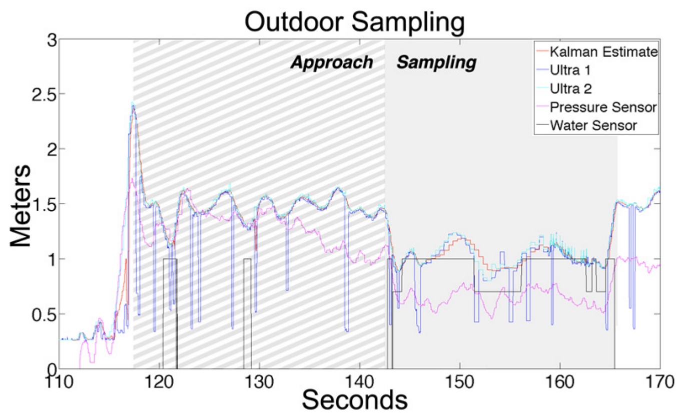

Fig. 12: Outdoor Sampling

For all indoor and outdoor trials, the UAV maintained an altitude at which the sampling system could collect water. Outside, the larger number of ultrasound spikes indicate additional noise, but the dual ultrasounds still allowed for successful altitude control. In the indoor tests, the water sensors only reached the bottom sensor, in part because the fishtank contains only $10cm$ of water, while outdoors, both the first and second water sensor are activated, but never the one at $70cm$ depth, indicating that the UAV got too close to the water. In the outdoor test, we noticed that the water sensor skimmed the surface as the UAV approached the sample location, which is reflected in Fig. 12. We observed a larger variation in x and y during outdoor sampling due to GPS accuracy, which impacts height as the UAV tilts as it tries to adjust its location. The outdoor tests confirm that it is possible to use the filtered height estimate while outdoors in calm conditions. Future tests will stress the system with higher winds and waves.

D. *Outdoor Sampling Effectiveness*

We performed initial experiments outdoors to test the effectiveness of the sampling system when controlled autonomously over water, using a script of GPS waypoints to sample from the same location three times on each test. The results of this test are shown in Table I. The success rate was 69%, with 7 of the 12 failures occurring on the first vial, where we later discovered the lid mechanism could stick closed (minor changes to the design could fix this issue). A further 3 of the remaining 5 “failures to fill” occurred on the third vial because the backup pilot took over control after deeming the UAV was trending too close to water, especially as the wind increased during the experiment. We believe pilot aborts will occur less frequently in the future as we improve hover stability in gusty conditions. Thirteen total sample trials were conducted, until all available batteries were discharged. Overall, within the wind and environmental constraints, the system demonstrated the ability to maintain altitude and retrieve samples.

VIII. Future Work

Water sampling has become a key activity in maintaining public health. Therefore, developing mechanisms for efficient and effective water monitoring will increase in importance over the coming decades. In this paper, we have demonstrated a novel mechanism for sampling water autonomously from a UAV. Although the mechanism described herein is a prototype, the preliminary findings show significant potential towards developing the foundations for a practical, useful water-sampling system.

Our future efforts include further operation and evolution of the prototype outdoors, especially in the presence of varying wind speeds and wave sizes, as well as with moving water. We also intend to explore how this platform might be used with adaptive sampling, and in combination with other sensing and sampling mechanisms deployed in bodies of water. We plan to examine the duration of the ‘flushing’ phase with our collaborators to ensure clean samples. Further, we would like to push some water analysis onto the platform to avoid collecting samples that do not meet required criteria. Finally, we will explore a line of inquiry pertaining to operational safety, as these systems are intended to be reliable tools in the hands of field scientists.

IX. Acknowledgments

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References

[1] W. K. Dodds, W. W. Bouska, J. L. Eitzmann, T. J. Pilger, K. L. Pitts, A. J. Riley, J. T. Schloesser, and D. J. Thornbrugh, “Eutrophication of U.S. freshwaters: Analysis of potential economic damages,” *Environmental Science & Technology*, vol. 43, no. 1, pp. 12–19, Jan. 2009.

[2] E. The United Nations Children’s Fund (UNICEF)/World Health Organization (WHO), Johansson and T. Wardlaw, “Diarrhoea: Why children are still dying and what can be done,” in *WHO Library Cataloging-in-Publication Data*, Jan. 2009.

[3] F. D. Wilde, D. B. Radtke, and G. S. (US), “National field manual for the collection of water-quality data: Field measurements,” 1998.

[4] A. J. Erickson, P. T. Weiss, and J. S. Gulliver, “Water sampling methods,” in *Optimizing Stormwater Treatment Practices*. Springer New York, Jan. 2013, pp. 163–192.

[5] M. Dunbabin, A. Grinham, and J. Udy, “An autonomous surface vehicle for water quality monitoring,” *Robotics and Automation (ACRA)*, vol. 13, 2009.

[6] N. A. Cruz and A. C. Matos, “The mares auv, a modular autonomous robot for environment sampling,” in *OCEANS 2008*. IEEE, 2008, pp. 1–6.

[7] J. Melo and A. Matos, “Bottom estimation and following with the mares auv,” in *Oceans, 2012*. IEEE, 2012, pp. 1–8.

[8] M. Rahimi, R. Pon, W. Kaiser, G. Sukhatme, D. Estrin, and M. Srivastava, “Adaptive sampling for environmental robotics,” in *2004 IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA ’04*, vol. 4, 2004, pp. 3537–3544 Vol.4.

[9] T. Merz and F. Kendoul, “Dependable low-altitude obstacle avoidance for robotic helicopters operating in rural areas,” *Journal of Field Robotics*, 2013.

[10] F. Kendoul, “Survey of advances in guidance, navigation, and control of unmanned rotorcraft systems,” *Journal of Field Robotics*, vol. 29, no. 2, pp. 315–378, 2012.

[11] K. Sreenath, N. Michael, and V. Kumar, “Trajectory generation and control of a quadrotor with a cable-suspended load–a differentially-flat hybrid system.” ICRA, 2013.

[12] A. H. Göktoğan, S. Sukkarieh, M. Bryson, J. Randle, T. Lupton, and C. Hung, “A rotary-wing unmanned air vehicle for aquatic weed surveillance and management,” in *Selected papers from the 2nd International Symposium on UAVs, Reno, Nevada, USA June 8–10, 2009*. Springer, 2010, pp. 467–484.

[13] A. D. Eaton and M. A. H. Franson, *Standard methods for the examination of water & wastewater*. American Public Health Association, 2005.

[14] K. Anderson and K. J. Gaston, “Lightweight unmanned aerial vehicles will revolutionize spatial ecology,” *Frontiers in Ecology and the Environment*, vol. 11, no. 3, pp. 138–146, 2013.

[15] “Robot Operating System.” [Online]. Available: http://www.ros.org

[16] “Ascending Technologies.” [Online]. Available: http://www.asctec.de

[17] “TCS micropumps, UK. Model M200S-SUB.” [Online]. Available: http://micropumps.co.uk/TCSM200range.htm

[18] “Maxbotix.” [Online]. Available: http://www.maxbotix.com

[19] “VICON.” [Online]. Available: http://www.vicon.com