Autonomous Aerial Water Sampling

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Abstract Obtaining spatially separated, high-frequency water samples from rivers and lakes is critical to enhance our understanding and effective management of fresh water resources. In this paper we present an aerial water sampler and verify the system in field experiments. The aerial water sampler has the potential to vastly increase the speed and range at which scientists obtain water samples while reducing cost and effort. The water sampling system includes: 1) a mechanism to capture three 20 *ml* samples per mission; 2) sensors and algorithms for safe navigation and altitude approximation over water; and 3) software components that integrate and analyze 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 results of outdoor experiments. We compare water samples from local lakes obtained by our system to samples obtained by traditional sampling techniques. We find that most water properties are consistent between the two techniques. These experiments show that despite the challenges associated with flying precisely over water, it is possible to quickly obtain water samples with an Unmanned Aerial Vehicle (UAV).

1 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 fresh water sources annually costs over $2.2 billion, but the full extent of the cost is poorly known due to insufficient

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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 tackle these limitations through the development of a UAV-based water sampling system with a focus on enabling *safe and reliable* in-the-field water sampling. Fig. 1 shows the system collecting a water sample. We designed the system based on input from our limnologist collaborators who specified that the system be carried and deployed by a single person, collect multiple samples within kilometer ranges, and acquire at least 20 *ml* per sample[1].

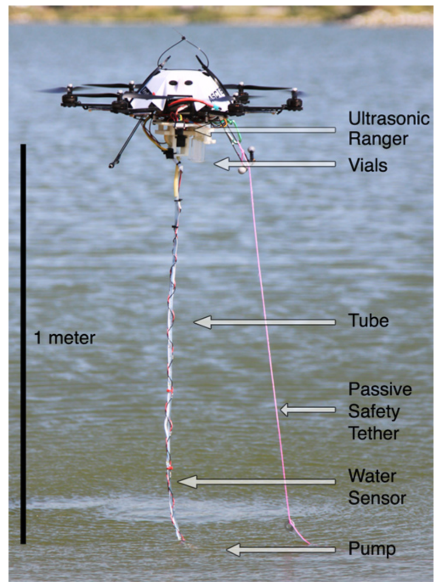


Fig. 1: UAV-Based Water Sampling.

Obtaining water samples from a UAV, however, poses 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 20 *ml* water samples per flight; 2) integrating and characterizing sensors on the UAV to enable reliable, low-altitude flight (1.0 *m*) over water; 3) testing the system both indoors in a motion-capture room as well as in the field at lakes and waterways; and 4) validating that key water chemical properties are not biased by using a UAV-based mechanism. 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.

[1] The quantity, 20 *ml*, is enough to perform most standard water chemistry experiments.

2 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 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. Underwater, Cruz *et al.*'s [6] [7] MARES AUV dives up to 100 *m* deep to 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 are good for long-duration sampling in deep or distant places. However, it is time-consuming and expensive to frequently re-deploy these systems. In contrast, our system can be carried in a backpack and quickly deployed to sample multiple disconnected water features from a single launch site. 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 Merz *et al.* [9], who show techniques for low-altitude flight in rural areas, whereas our focus is low-altitude flight over water but 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 commercially available radar altimeters are still 375 *g*, heavy for a micro UAV, and are accurate to only $\pm$ 0.5 *m*, below the requirements of our system. Optical methods are easily perturbed by ambient light, so instead we chose ultrasonic rangers.

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.

The Aquacopter [12] UAV lands in and takes off from calm water. We do not adopt this platform or land in the water because: 1) fast-moving water or waves might make it impossible to take off; 2) the sampling mechanism and battery enclosure would be complete sealed, making removal difficult and decreasing the efficiency of swapping vials or batteries; and 3) radio strength attenuates near the water's surface and we want the UAV and base station in constant contact.

Our work most resembles the low-altitude UAV presented by Göktoğan *et al.* [13], 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, since laser altimeters work poorly at short range over clear water, and we retrieve a liquid rather than depositing it. In addition, we focus on validating the utility of the system for water scientists.

3 Applications In Environmental Monitoring

Presently, limnologists and hydrochemists require water samples for lab analysis. They measure chemical properties of surface water, including phosphate, total phosphorus, 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 [14]. By facilitating data collection, lightweight UAVs, together with our collaborators, will improve, if not "revolutionize" spatial ecology [15]. 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 by increasing spatial and temporal resolution.

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

For example, our collaborators study the Fremont Sandpit lakes (see Fig. 2). Each numbered lake is groundwater connected, surface water disconnected, chemically distinct, and must be sampled separately. Currently, a team of three scientists tow a boat to the lake, 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. But in just two hours, one scientist with our UAV-system could sample all these lakes, enabling the possibility of capturing data with unprecedented spatiotemporal resolution.

4 Technical Approach

Through discussions with our hydrologist partners we derived a set of requirements for the aerial water sampler. First, it must capture at least three 20 *ml* water samples at predefined locations within 1 *km*. Second, it must be light and small enough to be carried by a single scientist, and sample autonomously once target locations are identified. Third, it must be reliable and safe to reduce cost and risk, since these are the primary barriers for adoption. Fourth, the new sampling system must not influence water properties. Addition requirements not addressed in the current work include a simple user interface for scientists to use and endurance and robustness to work in any climate. We chose to address first the core functionality of the system and save secondary requirements for future work.

We now describe how we address these requirements through: 1) mechanical design, including the UAV and sampling mechanism; 2) sensors for near water flight; and 3) the software system, including a discussion of the safety logic used to ensure the vehicle stays out of the water.

4.1 Design of UAV Water Sampling Mechanism

The water sampler is built onto an Ascending Technologies Firefly [16], a hexrotor with a maximum payload of 600 *g*. Total flight time is 15-20 minutes. The Firefly comes equipped with GPS, 3-axis accelerometers and gyroscopes, compass and an air pressure sensor. This UAV communicates with a human backup pilot using a radio link, and has two 2.4 *GHz* 802.15.4 radios for remote autonomous control and sensor feedback. To comply with local regulations regarding UAVs, we fly outdoors with a passive string tether connected to the frame of the vehicle and wrangled by a human operator. In practice, the tether limits the distance the UAV can travel but does not otherwise impact its mobility.

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 20 *ml* glass vials (Fig. 3). 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 (Fig. 3). The duration of the flushing phase is configurable, defaulting to 20 *s*, three times the duration required to fill a 20 *ml* vial[2]. The needle is connected to a 1.05 *m* 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.

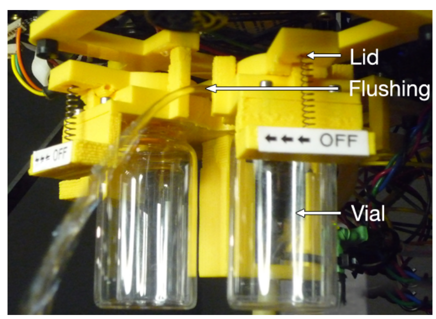


Fig. 3: Flushing the sample system.

[2] Initial experiments show that 20 *s* flushing avoids cross-contamination. We plan to more rigorously characterize this in future work.

4.2 Sensors for Near Water Flight

The UAV includes an onboard pressure sensor. To improve height estimation, we augment the UAV with ultrasonic rangers and water conductivity sensors. We use two Maxbotix MB1240-EZ4 ultrasonic rangers [18] pointing straight down and flanking the sampling mechanism 10 *cm* from the center to increase the likelihood of an unobstructed path to the water's surface, which might otherwise be blocked by the swinging tube and pump.

Each ultrasonic ranger samples at 10 *hz* and we offset their sample time by 50 *ms* to prevent interference. This also increases the rate that altitude information is acquired to 20 *hz*. This rangefinder is well-suited to rotorcraft because of its resilience to motor noise, ± 1 *cm* accuracy, and reliability below 3 *m*.

Water conductivity sensors are placed every 10 *cm* from the bottom of the sample tube, up to 50 *cm*, to ensure that the system knows when its too close to the water and also to regulate the pump. The pump must be submerged and primed prior to operation. An onboard controller turns on the pump only after being wet for more than 400 *ms* which allows it, as experimentally determined, to prime.

4.3 Software

The software system contains two sub-systems: 1) code on a control computer using the Robot Operating System [19] which handles low-level communication with the UAV, mission control, navigation, and high-level sampling tasks; and 2) onboard code on a custom built microcontroller 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 to detect unsafe water sampling or navigating conditions based on the sensor readings, and restart a mission. In total, the system includes about 7K lines of C, C++, and Python code.

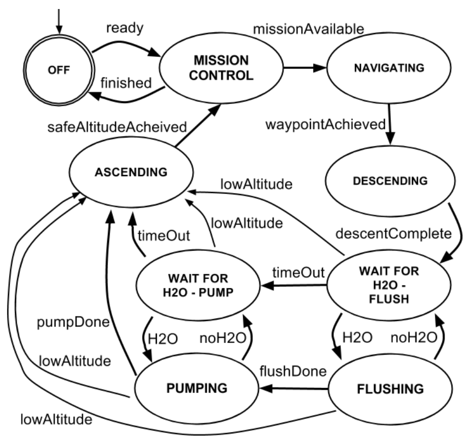


Fig. 4: Sampling States.

The flow of water sampling activities is shown in Fig. 4, and follows a clockwise pattern. Overall, the system receives a mission, navigates to a sample location, descends near to the water surface, waits for the water sensors to confirm that the pump is wet, flushes, pumps, ascends, and navigates either to the next sample location or returns to the landing location. 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.

5 Altitude Estimation Over Water

We form an altitude estimation in two ways: 1) at low altitude with a Kalman Filter of ultrasonic ranger and pressure sensor readings; and 2) at high altitudes with the pressure sensor plus and offset from the low-altitude Kalman estimate. In this section we characterize the ultrasonic sensors over water, discuss how the low altitude estimation is formed and then how the low and high altitude estimations are used to form a final altitude estimate.

The ultrasonic rangers are necessary because the pressure sensor alone drifts over time due to wind or changes in atmospheric pressure. We characterized the ultrasonic rangefinders over water by conducting indoor flight tests with ground truth from a Vicon motion capture system [20]. We tested their performance while flying over water. The results are show in Fig. 6, during which the UAV was over water, and the ultrasonic readings are shown offset by 15 *cm*, the height of the water in the fishtank. The data was gathered during autonomous flight, flying the UAV to 2 *m* above the fish tank, then descending to 1.5 *m* and 1.25 *m* before returning to 2 *m* and leaving the over water area. We placed acoustic foam over the fish tank (Fig. 5) to absorb the ultrasound readings so that the edge of the tank is not detected.

As seen in Fig. 6, the ultrasonics closely follow Vicon ground truth, although they lag slightly behind as the UAV descends. The lag is caused the latency of the ultrasonics, but it is less important for our system since we're most concerned with accurate readings when the UAV is hovering and since we limit the descent velocity

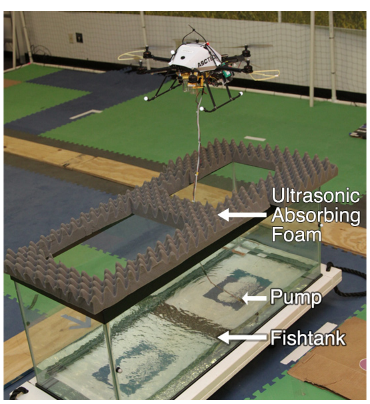


Fig. 5: Indoor Testbed for Water Sampling.

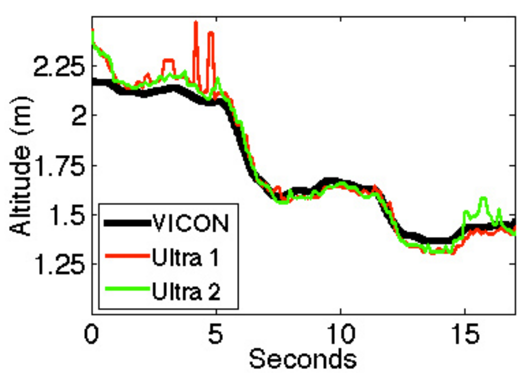


Fig. 6: Ultrasonic and Vicon Altitude Over water.

so that the system has more time to detect the water's surface. In extreme cases, the ultrasonics exhibit large spikes at longer ranges ($+2$ *m*), but this noise is usually brief and rarely affects both sensors simultaneously, so having more than one sensor is important to filter sporadic noisy readings. These experiments show that the ultrasonic sensors perform well over water on a flying UAV, especially when the UAV is hovering near the water's surface.

5.1 Kalman Filter Low-Altitude Estimation

At low altitude, we merge the pressure and ultrasonic readings using a Kalman Filter and shown in Fig. 7. The ultrasonics must be pre-filtered before entering the Kalman Filter since the swinging tube causes non-Gaussian noise. The current readings from the two ultrasonic sensors are evaluated based on variance during the last second and proximity to the current Kalman estimate. We choose the reading with least variance, closest to the current Kalman estimate, giving preference to proximity. If both or neither satisfy these conditions, we average them. While its rare to have faulty readings from both sensors, experimentally we have determined that even if there is continuous faulty data from the ultrasonics, the Kalman estimate quickly converges to a good estimate once a single sensor yields accurate readings.

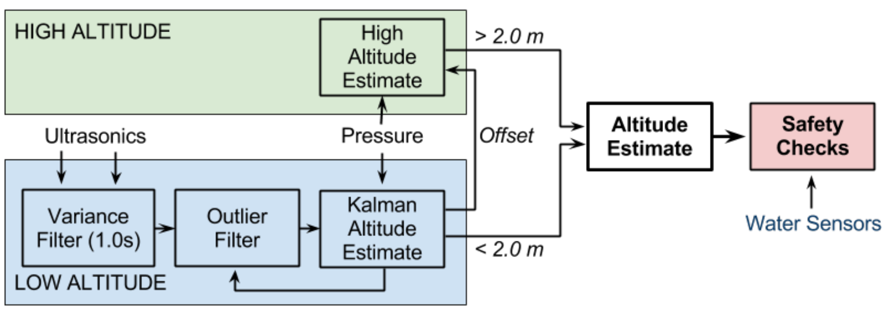


Fig. 7: Altitude Estimation Information Flow.

5.2 Final Altitude Estimate

The final altitude estimate uses the Kalman estimate at low altitude and the pressure sensor with an offset at high altitude as shown in Fig. 7. At low altitudes, the Kalman estimate is accurate enough to assure vehicle safety, while at high altitude, the pressure sensor is sufficient and if sensor drift forces the system below two meters, the low-altitude controller will take over. Anytime the vehicle transitions from low to high altitude, the pressure sensor is offset with the last best estimate from the Kalman Filter. When descending, we limit velocity so that the UAV can stop before coming within one meter of the water.

We enforce additional safety checks with the water sensors on the tube. If the water sensors indicate that the tube is too deep, then the UAV ascends to a safer altitude. The water sensor data is not directly added to the Kalman Filter both because they are slow (0.5 s) and also because occasional water droplets from the pump cause false readings. In the next section we validate this approach with indoor and field experiments.

6 Altitude Experiments While Sampling

We performed experiments indoors and outdoors to validate the altitude estimate while sampling. The indoor experiments verified that the Kalman filter-based altitude estimate closely tracked the Vicon ground truth. Outdoors, the location was a human-made waterway along Antelope Creek in Lincoln, Nebraska, USA. The water at this location is $1-2$ m deep. For these outdoor tests we chose a calm day with wind speeds measured at less than 0.27 ms^{-1} with a hand-held anemometer. Fig. 1 depicts the system operating outdoors.

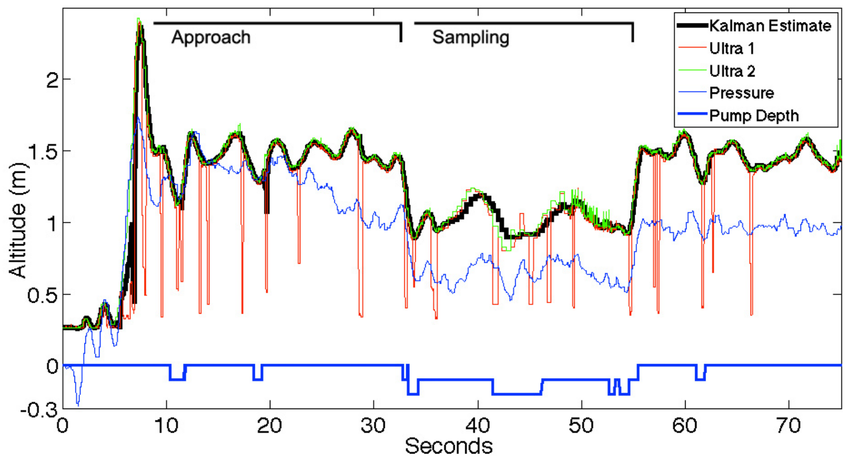


Fig. 8: Vehicle Altitude and Pump Depth While Sampling Outdoors.

We recorded the ultrasonic, pressure sensor, and Kalman-filtered height estimate, as shown in Fig.8. During this experiment the UAV always flew at low altitude. This figure shows the UAV while it ‘approaches’ the sample destination and the critical ‘sample’ stage when the UAV descends and maintains altitude to pump water. Compared with altitude tests indoors, the ultrasonic sensor readings had more spikes, indicating additional noise[3], but the dual ultrasonics still allowed for successful altitude control. The figure also shows the depth of the pump, as detected by the water sensors on the tube. Both the first and second water sensor are activated during sampling, but never the ones above. We noticed that the water sensor skimmed the surface as the UAV approached the sample location, which is reflected in Fig. 8. During the outdoor altitude tests, we observed a larger variation in x and y during

[3] The noise from Ultrasonic 1 in Fig. 8 is an extreme example, as there was faulty cabling. However, the altitude estimate tracks in spite of this noise.

sampling due to GPS inaccuracy, which impacts height as the UAV tilts as it tries to adjust its location. These tests confirm that our filtered altitude estimate works well at near proximity to water in calm conditions. Future tests will stress the system with higher winds and waves.

7 Water Sampler Effectiveness Experiments

We tested the water sampling system both indoors and outdoors. Indoors, we perform autonomous missions that launch the UAV to 2.0 *m*, fly over the fish tank (Fig. 5), descend to the sampling height where the pump is submerged, take a sample, and then ascend back to 2.0 *m*. 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 1 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 1 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 fishtank or the pump failing to self-prime.

Likewise, we performed outdoor experiments to test the effectiveness of the sampling system when controlled autonomously over water. We programmed the system to navigate to GPS waypoints and obtain three samples. The results of this test are shown in Table 1. The success rate for fully-filled vials was 69%, with 7 of 12 failures caused by a faulty lid mechanism which we have now fixed. Three of the remaining five "failures to fill" occurred on the third vial when the backup pilot took over control after perceiving that the UAV was trending too close to water, especially as the wind increased during the experiment. We believe pilot aborts will occur less

Table 1: Sampling Success Rate

Altitude	Trials	Samples	Full	$> \frac{1}{2}$	$< \frac{1}{2}$	% Full
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

frequently in the future as we improve hover stability in gusty conditions and as safety pilot confidence increases. 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.

8 Sampling Technique Comparison: Hand vs. UAV-Mechanism

We conducted an experiment to ensure that water samples collected by the UAV-mechanism exhibit similar water chemical properties as samples obtained through traditional hand sampling methods. Potential differences include those caused by pumping, transit through the tube, agitation during flight, and changes in water properties during the delay between sample acquisition and sample measurement on land. The UAV was not flown, but rather held by a human operator in a kayak to ensure that both the hand and UAV samples were taken at the same time and place.

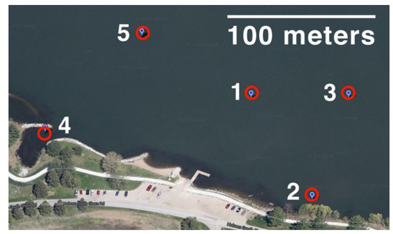


Fig. 9: Holmes Lake

In order to verify the consistency between manual and UAV-based sampling, we sampled at five locations on Holmes Lake, Lincoln, NE, USA. We collected two samples near shore and three closer to the middle of the lake, as shown in Fig. 9. At each location, we took three samples by hand and three with the UAV-mechanism for a total of fifteen samples by each method. Overall it took approximately 2 hours to collect this data due to the time to kayak, collect manual and UAV-mechanism samples, and to perform some on-site analysis and filtering. We estimate that collecting the samples with the UAV flying would take 20 minutes.

At each location we measured temperature, dissolved oxygen (DO)[4], sulfate, and chloride. By sampling both a dissolved gas and representative ions we can assess the suitability of the UAV-mechanism for scientific water sampling. Temperature and DO are measured at the sample location for the manual measurements and at shore once the UAV returns, since these properties change rapidly. Chloride and Sulfate ions are measured in the lab using equipment[5] which is not easily portable and these properties don't change rapidly after sampling and filtering. We measured DO as it is a key indicator of biological activity and because we suspected the UAV-mechanism might bias the measurement through degassing during pumping or continued photosynthesis during transit. Sulfate and chloride ions occur naturally in most water and their ratio in freshwater can indicate proximity to a saltwater source. But inland, chloride comes from many sources including lawn fertilizers and road salt. High

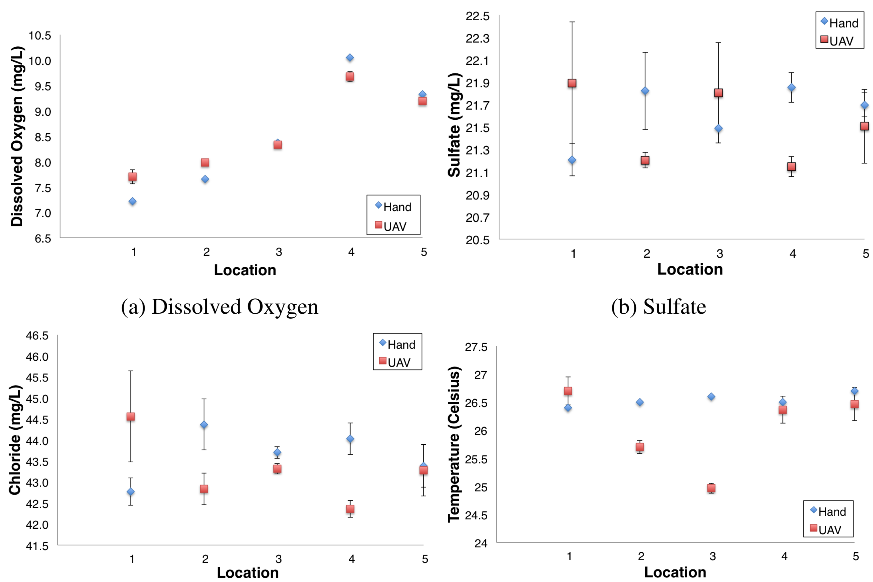
[4] For DO and temperature a single reading was obtained with the hand sensor at the location, but for the UAV-mechanism it was tested on each of the three samples.

[5] Lab measurements use a Dionex Ion Chromatograph AS14A, made by ThermoFisher

concentrations of chloride in organisms can induce osmotic stress, reduced fitness, or mortality.

We are primarily interested in verifying that the UAV-mechanism does not induce a bias in the measurements. Fig. 10a shows the DO as measured by hand at the location and with the UAV-mechanism. The values at the five sample locations are close and show the same general trend in all five locations, implying that the UAV-mechanism and delay (longer by kayak than by flying) has little impact on the DO. Also visible in this figure is the general upward trend between the sample locations. This was probably caused by increased photosynthesis over the two hours of data collection, although sample location may also play a role in this variation. For instance, location 4 is probably higher than the general trend because it is closer to an enclosed bay and therefore likely to have more plants near the surface. Obtaining samples quickly by UAV could help to disambiguate these factors.

Sulfate and chloride concentrations shown in Fig. 10b-10c revealed some differences between hand methods and the UAV-mechanism. These differences, however, can likely be attributed to typical sampling variation and neither indicates a strong bias induced by the UAV-mechanism. Further, the typical range for Sulfate in lakes is between $10-60\ mg/L$ [21] and for Chloride varies seasonally but usually is between $10-100\ mg/L$ [22], so the observed variation is minimal. We plan to perform additional field and lab tests to verify that these measurements are unbiased.



(a) Dissolved Oxygen

(b) Sulfate

(c) Chloride

(d) Temperature

Fig. 10: Water Chemistry measurements from Hand Sampling and UAV-mechanism. Points represent the average of three replicate measurements, and error bars indicate ± 1 standard error of the mean.

In contrast to the other measurements, Fig. 10d, shows that the temperature measured by hand at the sample location is nearly constant, while the temperature measured in samples from the UAV-mechanism changed during transit, especially at locations two and three. Future versions of system should measure water temperature at the sample location by mounting a temperature probe at the end of the pumping tube.

These experiments show the UAV-mechanism can collect samples that replace those collected be hand. The UAV system greatly reduces the effort and time to collect samples. This permits water scientists to obtain more samples within a single lake or river to develop a high-resolution map, for instance, after a rainstorm to identify the source of the influx of chemical or biological contaminates. In addition, reducing the collection time is critical since many water properties, such as DO, fluctuate within hours and using our UAV system would reduce collection time by nearly an order of magnitude.

9 Conclusions and Future Work

Water sampling has become a key activity in effectively managing our fresh water resources and maintaining public health. Developing approaches and systems 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 that requires significantly less effort than existing techniques and is nearly an order of magnitude faster. The system can safely fly close to water and collect three 20 *ml* samples per flight. We verified that the water properties of the samples collected by the UAV match those collected through traditional manual sampling techniques. This shows that this system can be used by water scientists to improve the spatiotemporal resolution of water sampling.

Our future efforts include further operation and evolution of the system outdoors, especially in the presence of varying wind speeds and wave sizes, as well as with moving water. We are in the process of implementing and evaluating the usability of a user interface for the limnologists and non-expert operators that balances manual control with autonomous behavior with the goal of maintaining system and operator safety. 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. In addition, 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. Finally, we are pursing approval from the US Federal Aviation Administration to conduct larger-scale outdoor tests at critical test sites identified by water scientists.

Acknowledgements We would like to thank our other limnologist and environmental engineering partners Dr. Michael Hamilton and Dr. Sally Thompson, for their continuous support of these efforts. We would also like to acknowledge the valued assistance Hengle Jiang, Christa Webber, Emily Waring, Dr. Seth McNeil, and the NIMBUS Lab. This work was partially supported by

USDA #2013-67021-20947, AFOSR #FA9550-10-1-0406, NSF IIS-1116221, NSF CSR-1217400, NDEQ grant #56-1131 and a development grant from ORED-UNL. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of these agencies.

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