# Bringing Unmanned Aerial Systems Closer to the Environment

Carrick Detweiler, John-Paul Ore, David Anthony, Sebastian Elbaum, Amy Burgin, Aaron Lorenz

**Increasingly, Unmanned Aerial Systems (UASs) are changing the way that scientists and practitioners collect environmental data. Current UASs, however, are largely relegated to collecting data while flying remotely, far away in the air. This article examines two case studies where micro-UASs fly in immediate proximity to the environment, enabling them to collect physical samples and capture sensor data that cannot be obtained at a distance. The first case study presents an aerial water sampler that flies to remote locations and dips a pump into the water to collect samples for lab analysis. The second case study examines a UAS that flies within a meter of crops to accurately measure their height. Each requires different sensors and methods specifically tailored to operating and interacting near the environment. This article evaluates the performance of these systems and also presents preliminary validation that they collect datasets that are compatible with those gathered by existing approaches. Futhermore, it distills some common underlying design and operating principles shared by UASs aimed at working close to the environment. Finally, this article concludes that in spite of numerous pending challenges, UASs that directly interact with the environment will transform the way environmental data is collected.**

**Environmental Practice 17: 188–200 (2015)**

Unmanned Aerial Systems (UASs) are having a huge impact on many fields and have already been used in preliminary studies to create aerial surveys and photo-mosaics (Lizarraga et al., 2008; Schwager, Julian, and Rus, 2009; Watts et al., 2010), measure atmospheric conditions (Jensen et al., 2009; Wegener et al., 2004), monitor wildfires (Alexis et al., 2009; Ambrosia et al., 2011), and monitor agricultural fields from high altitudes (Lelong et al., 2008; Rango et al., 2006). The impact of UASs will continue to increase as they become less expensive, more common, and better integrated into the national airspace. In the near future, scientists and policy makers will use data collected from UASs to improve field studies and to make policy decisions.

Current UASs primarily rely on remote observation sensors, such as cameras or hyper-spectral imagers, which operate at high altitudes, far above ground obstacles. However, the next generation of UASs will have improved sensors and systems to allow much closer interaction with the environment, enabling novel applications. This is especially true for the multi-rotor, hovering type of micro-UASs (typically under 3 kg) that can precisely move through the environment, avoiding obstacles and positioning their sensor payloads closer to objects of interest. In the future, we expect scientists and practitioners to launch these vehicles from roadsides and small clearings to quickly fly to hard-to-access locations. Once in position, the UASs will do everything from clipping a leaf off of a plant, to collecting water samples, to installing remote sensors for long-term monitoring of the environment. Scientists will be able to quickly gather datasets with increased spatiotemporal resolution and with less impact on fragile environments than foot or vehicle traffic.

In this article, we discuss recent advances that enable close interaction between UASs and the environment. We then present two case studies from our research group that require close interactions with different, unstructured environments, while safely and accurately maintaining the proper distance from obstacles. The first study is a

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 doi:10.1017/S1466046615000174

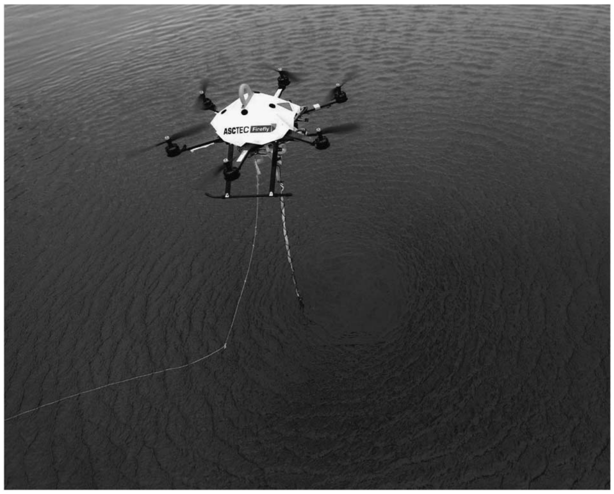

**Figure 1.** Aerial water sampling UAS

micro-UAS that can precisely fly over water to collect water samples for ex situ analysis (Figure 1). The second is a micro-UAS that flies within 1 m of crops to measure physical properties, such as crop height as shown in Figure 6, that cannot be easily collected with remote sensors or manual measurements. While both studies expand the capabilities of UASs to fly close to the environment, the sensors and methods required are different in the two case studies. The first study uses a pair of ultrasonic range finders and other sensors, while the second relies on a two-dimensional (2D) laser scanner. Picking the correct type of sensing and the proper methods is critical for these types of close interactions, especially when considering the limited payload and flight time of the vehicles. Beyond developing the systems, it is important to characterize and verify that data collected from the air correlate with traditional methods. After examining these case studies, we then discuss the potential impact of these systems and technical and regulatory limitations that must still be overcome to enable UASs to fly and interact with the environment.

## Recent Advances in UAS-Environmental Interaction

Bringing UASs closer to the environment is an active and intense area of research, especially in the robotics community. In these areas UASs are also sometime known as Unmanned Aerial Vehicles (UAVs), Micro Aerial Vehicles (MAVs), flying robots, or, colloquially, drones. Researchers recently demonstrated novel construction techniques, grasping and manipulation, outdoor obstacle avoidance, and near-range environmental sensing and sampling applications.

Multi-rotor UASs have been used in construction tasks with spools of cable to bind poles together and "weave" semi-rigid structures in the spaces between fixed anchors (Augugliaro et al., 2013). UASs with simple one degree-of-freedom (DOF) grippers have been used to construct "snap-together" bar-structures using a team of UASs under centralized control (Lindsey, Mellinger, and Kumar, 2012), while other groups extend the complexity and capability of these bar-construction tasks by using a heavier 6DOF robotic arm (Cano et al., 2013). Both of these efforts rely on indoor motion-capture systems for millimeter-precision position information, but recent efforts realized grasping outdoors with cameras systems mounted to both the UASs' body (for situational awareness) and the end-effector of a 7DOF arm (for grasping accuracy) (Heredia et al., 2014).

Other grasping applications include efforts to turn valves with multi-rotor UASs (Korpela, Orsag, and Oh, 2014), and some vehicle designers explore rotor configurations specially designed to increase wrenching force (yaw) exerted by micro-UASs (Jiang and Voyles, 2014). Nearly all techniques for grasping approach their targets slowly and deliberately. One notable exception is recent avian-inspired work (Thomas et al., 2013) in which a UAS swoops down and snatches a target while moving at speeds up to 3 m/s. Although these techniques were originally demonstrated using motion-capture systems, new work in visual servoing aims to take fast grasping into unstructured, outdoor environments (Thomas et al., 2014).

Advances in the application of visual-inertial odometry allow a 1.9 kg UAS, equipped with stereo cameras, a laser scanner, and Global Positioning System (GPS), to navigate autonomously through outdoor and indoor environments including parks and garages, all at low altitude (Shen et al., 2014). Another approach using visual-inertial odometry with a rotating laser scanner autonomously explores rivers and avoids obstacles like overhanging branches and bridges without using GPS (Jain et al., 2013). Currently, these efforts enable UASs to avoid obstacles and operate in close proximity to the environment, but they consume nearly all their useful payload with the sensors required to navigate in their environment.

In the noxious plant-management domain, a weed-spraying small-scale helicopter uses cameras to relay images of potential weeds to human experts who identify invasive species for herbicide (Göktoğan et al., 2010). All of these efforts and others are advancing the ability of UASs to closely and safely interact with the environment.

## Case Study: Unmanned Aerial Water Sampling

Collecting water samples from small lakes, streams, and ponds is extremely labor intensive for limnologists (surface-water scientists) yet critical to unlocking basic questions about water cycles, transport pathways, and the impact of our agricultural practices on the water systems that supply drinking water to our cities. Currently, it is possible to automate in situ sensing by deploying long-term sensors or using mobile sensors affixed to Autonomous Surface Vehicles (ASVs) (Dunbabin, Grinham, and Udy, 2009) or Autonomous Underwater Vehicles (AUVs) (Bird, Sherman, and Ryany, 2007; Cruz and Matos, 2008). However, surface vehicles must overcome barriers such as dams and land between sampling locations and then return to a boat launch location, limiting ease-of-use in ad hoc sampling for smaller water bodies. Additionally, many water properties, such as phosphate, total phosphorus, nitrate/nitrite, nitrogen, and ammonia content, as well as biological properties (e.g., presence of microcystins), cannot be easily measured in the field because sensitive lab equipment is not yet portable and, therefore, must be measured by collecting and transporting field samples to the lab, sometimes called ex situ analysis. Therefore, there is still a strong reliance on grab sampling (e.g., dipping a bottle off the side of a kayak) (Wilde and Radtke, 1998) to monitor and analyze water quality. Statically deployed water-collection systems exist (Erickson, Weiss, and Gulliver, 2013), but these types of systems are relatively slow, spatially restricted, costly, difficult to deploy, and must be installed at every sampling location.

We have developed an aerial water-sampling system (Ore et al., 2014) that can be quickly and safely deployed to reach varying and hard-to-access locations, that integrates with existing static sensors, and that is adaptable to a wide range of scientific goals. In this section we start by discussing the aerial water sampling system and the methods we developed to enable close interaction with water in moderate winds. We also present our preliminary analysis of the sampling system to verify that we can obtain scientifically valid results with this system.

### UAS Platform and Water-Sampling System

The water sampling system is mounted to an Ascending Technologies Firefly UAS and is shown in Figure 2. The Firefly is a hex-rotor UAS (flight is possible if a single motor fails) with a weight of 1.6 kg, a flight time of approximately 20 minutes, and a maximum speed of 15 m/s. The Firefly has an onboard GPS, three-axis accelerometers and gyroscopes, a compass, and a barometric altimeter. It can be programmed to operate autonomously or can be remotely controlled by a computer or human pilot. For compliance with United States (US) Federal Aviation Administration (FAA) requirements, we have obtained a Certificate of Waiver or Authorization (COA) for outdoor autonomous flight at our field locations. Our COA stipulates that we have a human backup pilot for the system within line-of-sight to the system at all times.

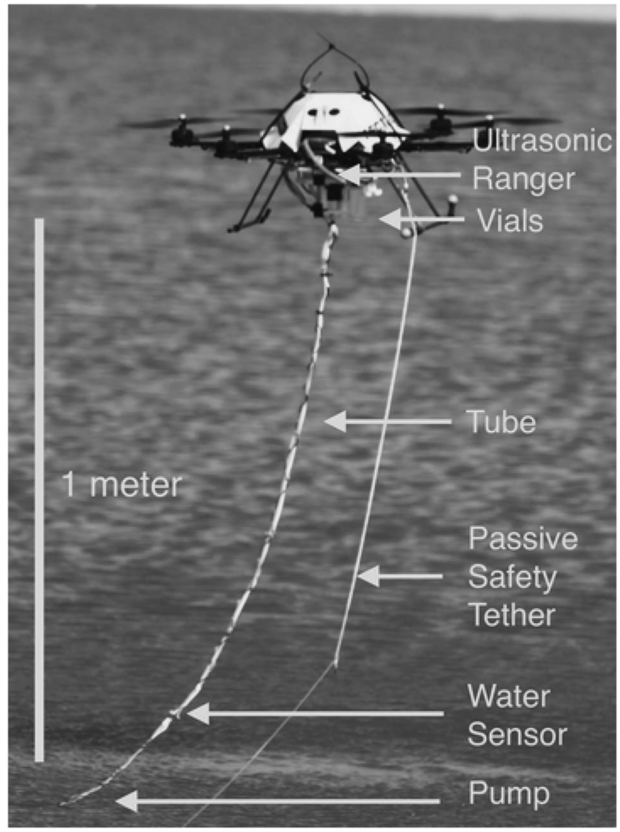


**Figure 2.** UAS-based water sampling

The water-sampling apparatus is a separate unit connected to the bottom of the Firefly. As shown in Figure 2 the water sampler consists of a three-dimensional (3D) printed plastic chassis that holds three 20 ml sample vials or a single large 100 ml sample vial. Ultrasonic range finders[1] are attached to the bottom of the UAS to precisely estimate the UAS's altitude. A tube, pump, and regularly spaced simple conductivity sensors dangle beneath the UAS. The ultrasonic sensors, conductivity sensors, and onboard altimeter enable precise height estimation over water, as discussed in the "Flying Close to the Water" section. When configured with three sample vials, a small servomotor can select the vial that is filled. In all configurations, the servomotor purges the pump and tube system by pumping water overboard. In addition, on-board sensors can be added to sense water attributes such as conductivity, temperature, dissolved oxygen, and others in real time.

## Methods

In this section we discuss our approach to safely flying close to the water in windy conditions, which is required when collecting water samples. We then discuss the experimental setup we used to compare the water collected by the aerial water sampler versus traditional manual techniques.

### *Flying close to the water*

Flying near water is dangerous to the UAS because water can damage the electrical and mechanical systems, yet flying near water is necessary for sample collection. Flying close to the water is difficult because the UAS does not come equipped with sensors to detect its surroundings, especially anything below it. More specifically, to fly close to water, we need an accurate estimate of the altitude above the water. The built-in barometric altimeter readings can drift several meters during a 20-minute flight and cannot be trusted during sustained operation over water. Similarly, while GPS provides sufficient horizontal accuracy to fly to a location over water, GPS does not provide good altitude estimates.

Laser-based scanners and rangefinders have been used to control UASs over unknown terrain, but have poor performance over water (Jain et al., 2013) due to reflections and refractions. Radar systems can operate over water and land but are either too large or inaccurate for a micro-UAS. Instead, we chose ultrasonic rangers and water conductivity sensors, both of which are under $50 and lightweight, to improve our height estimation. We mount the ultrasonic rangers pointing straight down and flanking the sampling mechanism 10 cm from the vehicle's center for a clear view of the water that is unimpeded by the sample-collection mechanism. We place water conductivity sensors every 10 cm from the bottom of the tube, up to 50 cm, to allow us to detect how deep the tube is in the water. The water conductivity sensors used for height estimation are exposed wires that let us determine if it is in water, but these sensors are not calibrated for precise conductivity readings.

The ultrasonic rangers exhibit three kinds of noise that we must account for when using them to form an altitude estimate. Specifically, the ultrasonic rangers have: (a) non-Gaussian spikes above 1.85 m or when the UAS has larger pitch and roll, (b) non-Gaussian noise when the tube swings in front of the sensor, and (c) Gaussian sensor noise. To account for the first, when the ultrasonic sensor readings exceed 1.85 m, we instead use the pressure sensor altimeter. For the swinging tube, we do not model the non-Gaussian noise and assume that at any time, the dangling pump will occlude only one of the two sensors. We also assume the two sensors yield nearly identical values when not occluded because of their physical placement. We employ a scoring heuristic to pre-filter the ultrasonic readings.

To determine the final altitude, we developed an estimation procedure that is outlined in Figure 3. To choose between the pair of ultrasonic range readings, we use a scoring heuristic. We give strongest preference to values within the maximum range (<1.85 m) and close to the prior height estimate (within 0.075 m) because we do not command fast height changes. If both ultrasonic sensors satisfy these, then we give preference to the sensor with the lower variance over the last second, unless both have a variance of less than <0.08 $m^2$, in which case we average the readings.

We then take the reading from the preferred ultrasonic sensor (or the average) and input this into a Kalman filter that fuses this value with the onboard pressure sensor-based altimeter. The Kalman filter estimates the current altitude

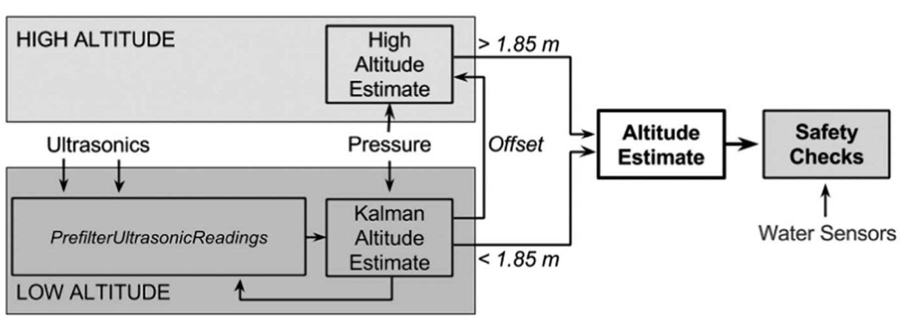


**Figure 3.** Altitude estimation information flow

above the water and a calibration parameter for the pressure sensor altimeter that corrects for its drift. If both ultrasonic sensors give poor data or we fly higher than 1.85 m (the maximum good range for these sensors), then we use the pressure sensor altimeter temporarily until we obtain good readings again or get closer to the water. As a final safety check, we always monitor the conductivity sensors to verify that the tube is not too deep in the water. If the upper-most sensor detects water, indicating the UAS is within 50 cm of the water, we abort and return to a higher altitude.

We wish to evaluate the performance of our altitude estimation approach in windy conditions. The Firefly base platform is specified by the manufacturer to operate in winds up to 10 m/s; however, this is in open environments away from the ground. We foresee several possible challenges when flying close to the water, including: (a) wind causing larger than normal changes in air pressure that will impact the barometric altimeter, (b) wind blowing the sampling tube and pump and possibly changing the height above the water required to obtain water samples, and (c) strong winds near the ground changing the flight dynamics of the vehicle.

To evaluate the performance of the altitude estimation system while flying close to the water in wind, we conducted outdoor tests in which the vehicle descended to the water surface, sampled, and ascended back to an altitude of 4 m, then repeated the sampling twice more in each mission. During this experiment, the computer controlled the altitude and yaw, while a human pilot controlled x and y movement because of the narrow profile of the water feature at our outdoor test facility (<3 m, about the same width as GPS error). During the experiment, we changed the target altitude after each trial so that as the wind changed during the day, we could collect data at each target altitude across a range of wind speeds. We discuss the results of these tests in the “Flying Close to the Water in Wind” section.

*Manual sampling comparison*

We have collected hundreds of water samples from ponds and lakes in Nebraska, US. In this section we discuss the methods we have used to evaluate how the aerial sampling approach compares to traditional hand sampling. We are specifically interested in chemical and physical properties and that the UAS water sampling mechanism does not introduce bias in dissolved ions or gasses. Some potential differences could be 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. For this experiment, we did not fly the UAS, but rather held the sampling apparatus by hand in a kayak to ensure that both the hand and UAS samples were taken at the same time and place.

In order to verify the consistency between manual and UAS-based sampling, we sampled at five locations on Holmes Lake, Lincoln, Nebraska. We collected two samples near shore and three closer to the middle of the lake, as shown in Figure 4. At each location, we took three samples by hand and three with the UAS mechanism for a total of fifteen samples by each method. Overall it took approximately two hours to collect these data due to the time to kayak, to collect manual and UAS-mechanism samples, and to perform some on-site analysis and filtering. We estimate that collecting these same samples by the UAS would take 20 minutes.

At each location we measured temperature, dissolved oxygen (DO)[2], sulfate, and chloride. By sampling both a dissolved gas and representative ions, we can assess the suitability of the UAS mechanism for scientific water sampling. Temperature and DO are measured at the sample location for the manual measurements and at shore once the UAS returns because these properties change rapidly. Chloride and sulfate ions are measured in the lab using equipment[3] that is not easily portable because these properties do not change rapidly after sampling and filtering. We measured DO as it is a key indicator of biological activity and because we suspected the UAS 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. However, inland, chloride comes from many sources including lawn fertilizers and road salt.

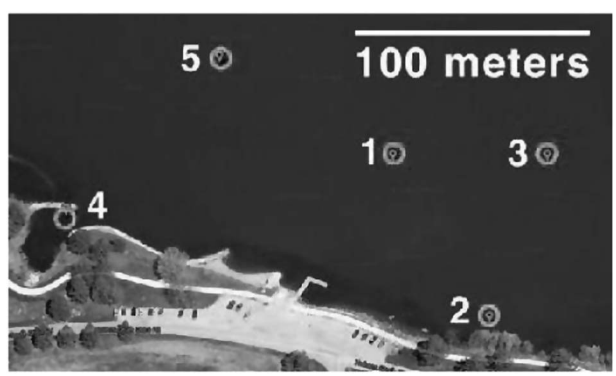


**Figure 4.** Lake sample locations

High concentrations of chloride in organisms can induce osmotic stress, reduced fitness, or mortality. Results from these experiments are presented in "the Comparison to Manual Sampling" section.

## Results

In this section we discuss the results of our experiments in flying close to the water in winds and the comparison of our aerial water sampling approach versus manual sampling.

*Flying close to the water in wind*

In the "Flying Close to the Water" section, we discussed our altitude estimation method and our experimental approach to verify this method. In this section, we present the results. We conducted 75 trials of three samples each over the course of three consecutive days for a total of 225 samples. We measured the wind speed using a portable weather station affixed to a tripod situated 5–6 m from the sample location at 2 m above the ground and averaged the results over the course of each sampling experiment. During these experiments we observed winds of up to 5.8 m/s. We tested five target altitudes above the water from 0.72 to 1.12 m in 0.10 m increments. The target heights were chosen to maintain a safe distance from the water, while being close enough to fully submerge the sample pump in the water.

Table 1 presents the results for these experiments in which a target altitude is given and we report on the minimum altitude for different wind speeds. We chose ranges of wind speeds so that each cell has at least four samples. As wind speed increases, we tend to get somewhat closer to the water at some point during sampling. Looking at this in more detail, from 0.0 to 4.5 m/s there is only a 0.05 m difference between the minimum altitude reached. Moving up to the next wind speed group, however, shows a larger drop of an additional 0.06 m lower minimum altitude and again a slight decrease when moving to our fastest wind tests. The cause of this lower minimum altitude is likely a combination both of our altitude estimate and the height control system of the UAS.

Subjectively, for higher target altitudes of above 1 m, the vehicle is sufficiently stable and remains far enough away for us to consider it safe to collect water samples in winds up to nearly 6 m/s. At our lowest tested altitude of 0.72 m in the strongest winds, it gets close enough to the water that it would be difficult for a human backup pilot to recover the vehicle in case of an emergency.

**Table 1.** Minimum average altitude by wind speed and target altitude.

| | Average Minimum Altitude (m) | | | | | |
|---|---|---|---|---|---|---|
| | WIND SPEED (m/s) | | | | | |
| TARGET ALTITUDE (m) | 0 – 2.7 | 2.7 – 3.5 | 3.5 – 4.5 | 4.5 – 5.3 | 5.3 – 5.8 | TOTAL |
| 0.72 | 0.48 | 0.49 | 0.43 | 0.43 | 0.35 | 0.43 |
| 0.82 | 0.56 | 0.60 | 0.52 | 0.45 | 0.43 | 0.51 |
| 0.92 | 0.69 | 0.71 | 0.54 | 0.61 | 0.51 | 0.61 |
| 1.02 | 0.75 | 0.76 | 0.77 | 0.55 | 0.65 | 0.70 |
| 1.12 | 0.88 | 0.88 | 0.86 | 0.78 | 0.77 | 0.83 |
| TOTAL | 0.67 | 0.69 | 0.62 | 0.56 | 0.54 | |

*Comparison to manual sampling*

We are primarily interested in verifying that the UAS mechanism does not bias the measurements. Figure 5a shows the DO as measured by hand at the location and with the UAS mechanism. The values at the five sample locations are close and show the same general trend in all five locations, implying that the UAS mechanism and the 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 four 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 UAS could help to disambiguate which factors cause these differences.

Sulfate and chloride concentrations shown in Figure 5b,c revealed some differences between hand methods and the UAS mechanism. These differences, however, can likely be attributed to typical sampling variation and neither indicates a strong bias induced by the UAS mechanism. Further, the typical range for sulfate in lakes is between 10 and 60 mg/L (Orem, 2004) and for chloride varies seasonally but usually is between 10 and 100 mg/L (Dodds, 2002) so the observed variation is minimal. We plan to perform additional field and lab tests to verify that these measurements are unbiased.

In contrast to the other measurements, Figure 5d shows that the temperature measured by hand at the sample location is nearly constant, while the temperature measured in samples from the UAS mechanism changed during transit,

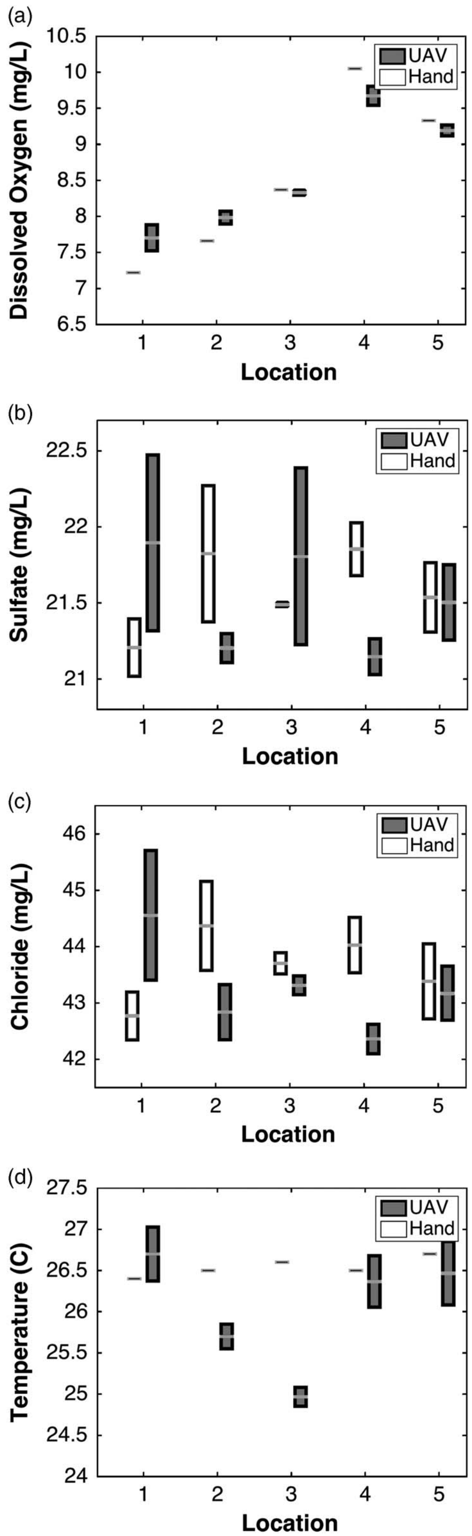


**Figure 5.** Water chemistry measurements from hand sampling and UAS mechanism. Points represent the average of three replicate measurements, and error bars indicate ± 1 standard error of the mean.

especially at locations two and three. Future versions of the 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 UAS mechanism can collect samples that resemble those collected by hand. The UAS system, however, 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 after a rainstorm, for instance, 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 UAS system would reduce collection time by nearly an order of magnitude.

## Case Study: Low Flying Crop Surveying

One of the largest potential markets for UASs is in agriculture due to the wide open and sparsely populated areas where it will be easier to obtain regulatory approval for operation. Current UASs are already improving modern agriculture production and research by providing data at higher temporal and spatial resolution scales and lower cost than traditional collection methods such as manned aircraft and satellites (Berni et al., 2009; Soria-Ruiz, Fernandez-Ordonez, and Woodhouse, 2010). Significant manual effort, however, is still required when practitioners need more detailed information on physical properties of their crops, such as crop height information that is used to assess crop development and plan treatments (Aziz et al., 2004). These measurements are currently obtained through manual measurement or by driving heavy equipment through the field. These collection methods are time consuming and damaging to the crops and as such, are not regularly used (Shrestha et al., 2002; Shrestha and Steward, 2005; Wolkowski and Lowery, 2008).

We have developed a low flying UAS, shown in Figure 6, that is equipped with a downward facing laser scanner that can measure crop height and canopy properties (Anthony et al. 2014). The crop surveying UAS flies within 4 m of the ground, and less than 1 m from the crops, to obtain crop height measurements that are with 5 cm of those collected by hand. This enables fast surveying of fields with a UAS that is small enough to carry in a backpack and into a field. Flying this close to the crops is challenging as the plants' heights vary across a field, and we must measure both the plants' tops and location of the ground. In this section, we start by discussing the crop surveying UAS system we have

**Figure 6.** Crop surveying UAS

developed. We then discuss the methods we have developed to fly close to the crops and present results of experiments that verify the system.

## Crop Surveying System

Figure 6 shows our complete system operating over a field. It is based on the same Firefly platform used with the water sampler and discussed in the "UAS Platform and Water-Sampling System" section. The UAS is equipped with a Hokuyo URG-04LXUG01 2D laser scanner, mounted in a downward facing configuration under the UAS, as shown in Figure 7a. The laser scanner produces a 240° scan at 10 Hz, with an angular resolution of ≈ 0.352°, for a total of 683 range readings per scan. The scanner has a maximum range of 5.6 m. Figure 7b shows an illustration of the types of readings we obtain from the corn. The 2D laser scanner returns a small slice of the field in each scan, and the vehicle's motion creates a 3D view of the field.

The scanner is intended for indoor operation, but our experiments show that the downward facing configuration mitigates sunlight interference with its operation, and the scanner can function outdoors. In addition, the scanner has an integrated filter that indicates which ranges are invalid. An onboard computer system interfaces to the scanner and the Firefly's control systems to process the laser scans onboard and autonomously fly the vehicle without a human operator. To satisfy the conditions of our COA, a safety pilot is present to control the UAS in emergencies. In the following sections, we show how the onboard GPS, inertial measurement unit (IMU), and laser scanner can control the UAS's height and collect valuable scientific information.

## Methods: Flying Close to Crops and Estimating Height

There are a number of reasons for operating this system close to the crops. First, low-cost laser scanners have range limitations that require flying a UAS close to the crops. Second, flying close to the crops increases the spatial resolution of the data. Figure 7b shows an illustration of how the 2D laser scan intersects with the crops and ground. Flying close to the crops increases the likelihood of obtaining a reading that hits the ground (only the dashed red line in the figure intersects the ground) and the tops of the plants, which is critical to maintain the correct distance from the tops and to estimate the height of the crops. Finally, future experiments will use this high spatial-resolution data to estimate plant parameters such as leaf density, angle to the stalk, and damage from weather or pests.

Flying close to the crops and estimating the crop height are tightly coupled problems. Our approach is to maintain an estimate of both the height of the UAS from the ground and also the height of the UAS above crops. Both distances must be estimated, not only for the scientific mission but to control the height of the vehicle. If the UAS only attempts to follow the tops of the crops, it risks descending into gaps in the foliage. In phenotyping trials, there are sudden differences in the crop height where plant varieties change, and operating at a known safe altitude over the ground is safer and simpler than following the tops of the crops. Thus, we always want to ensure we maintain both a minimum distance from the ground and a minimum distance away from the tops of the crops.

Converting the laser scan information into a crop height and UAS-altitude estimate is a multi-step procedure. The first step is to only extract valid range readings that are within the 90°-downward range of the laser scanner shown in Figure 7a. This eliminates readings that could not have possibly reached the ground and limits interference from the sun. The roll and pitch data from the IMU is used to decompose the range readings from the scanner into vertical and horizontal distance components that are relative to the UAS body. The results of these steps are shown in Figure 7c, which is a sample outdoor scan.

Examining Figure 7c, which also shows the true ground and crop top heights, we can see that a small number of readings reach the ground and many are at the top of the crops. Based on this, our method sorts the range readings and uses experimentally determined percentiles, $p_g$ and $p_c$, to pick the ranges that correspond to the ground and the top of the crops, respectively. The resulting height estimates are still

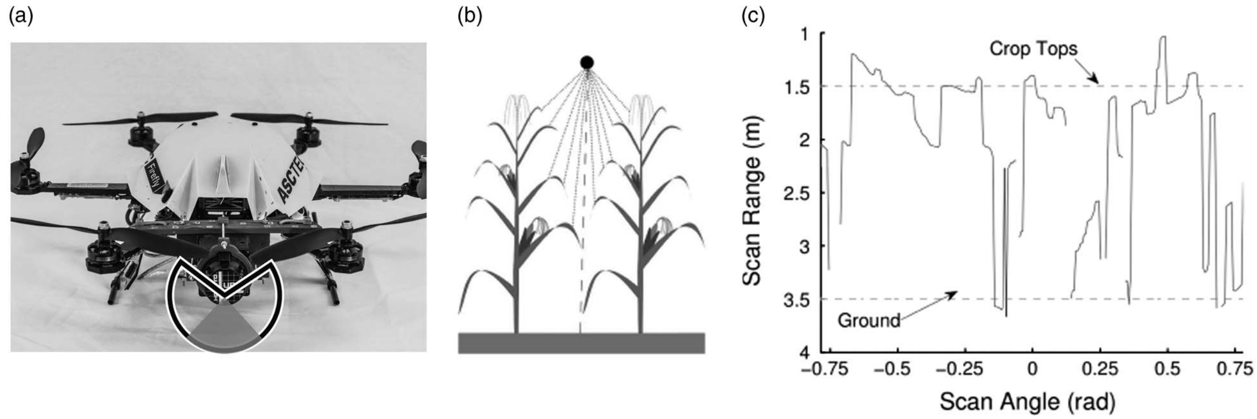


**Figure 7.** (a) UAS with laser scanner with 90° scan angle in red, (b) Illustration of UAS measuring corn, (c) sensor readings from corn field.

somewhat noisy and non-Gaussian, but the noise is mostly eliminated using a one-dimensional median filter.

A Kalman filter then fuses the ground distance estimate and information from the barometric altimeter to produce an altitude estimate, similar to how the water sampler fuses ultrasonic and barometric pressure information. The UAS is operated at a target altitude that is lower than 4 m, but more than 0.5 m above the expected crop height. This ensures that the UAS will maintain a safe separation between itself and the crops, while ensuring that all laser readings have a chance to reach the ground.

To evaluate the performance of the ground and crop-height estimation systems, we performed a series of flights indoors and outdoors over nearly full-grown corn crops. Indoors, we used simulated corn plants with a mean height of 0.967 m and a standard deviation of 3.74 cm. Outdoors, we selected a location in a phenotyping trial with a size of $3 \times 10$ m. A trained researcher measured the heights of 20 random plants in this area to serve as a ground truth. The height of the corn from the ground to top node on the plant varies between 1.98 and 2.26 m, with a mean height of 2.108 m and a standard deviation of 8.28 cm. The height from the ground to the tassel of the same plants ranged between 2.33 and 2.65 m, with a mean of 2.51 m and a standard deviation of 8.61 cm. We present the results of these trials in the next section.

## Results: Flying Close to Crops and Estimating Height

In this section, we analyze the results of the indoor and field experiments for crop height estimation. Because we do not have ground truth for the UAS' altitude, we instead compare the estimated crop height to the true crop height as this computation also requires an accurate ground estimate. We focus on the impact of the parameters $p_g$ and $p_c$ that control the ground and top of plant estimates. Table 2 summarizes the impact of different values for $p_g$ and $p_c$ on the crop-height estimate. The first row is the result of taking the two extreme points of each scan, highest and lowest, and using the difference as the crop-height estimate. This produces unacceptable results, as the outdoor crop-height estimate is 0.77 m larger than the actual crop height. This is the result of the tassels of the corn and tall corn leaves producing estimates of the plants' tops that are closest to the UAS, as well as noise in the outdoor environment. The ground estimate is also overestimated as it captures holes in the ground and furrows in the field, producing long-range scan estimates. The indoor data are similarly affected by noisy measurements and overestimates the artificial plant heights. Despite changing the UAS's position relative to the crop, the system was still able to form an accurate height estimate.

As more data are filtered from the scans, the crop-height estimates converge to the actual values. Of particular interest are the values around $p_g = 0.95$. With this parameterization, we can see that rejecting a small amount of the close scans to the UAS, $p_c = 0.02$, produces a crop-height estimate that is within 4 cm of the true value for the outdoor field. This parameterization also accurately estimates the indoor testbed's height.

Table 2 shows that the system is more sensitive to changes in $p_g$ than to $p_c$ in the outdoor setting. We conjecture that this is due to the dense upper-canopy returns that are a good estimator for the top of the crop. On the other hand, very few samples reach the ground, so the few samples reaching the ground have a high probability of being

**Table 2.** Impact of Estimation Parameters on Crop Height Estimates.

| $p_g$ | $p_c$ | Est. Indoor Height (m) | Est. Outdoor Height (m) | Indoor Error (m) | Outdoor Error (m) |
|---|---|---|---|---|---|
| 100 | 0 | 1.0545 | 2.8810 | 0.0875 | 0.7730 |
| 99 | 1 | 1.0412 | 2.5026 | 0.0742 | 0.3946 |
| 99 | 2 | 1.0335 | 2.4601 | 0.0665 | 0.3521 |
| 99 | 5 | 0.9888 | 2.3808 | 0.0218* | 0.2728 |
| 95 | 1 | 1.0219 | 2.1849 | 0.0549 | 0.0769 |
| 95 | 2 | 1.0133 | 2.1440 | 0.0463* | 0.0360* |
| 95 | 5 | 0.9690 | 2.0625 | 0.0020* | −0.0455* |
| 90 | 1 | 1.0040 | 1.9077 | 0.0370* | −0.2003 |
| 90 | 2 | 0.9956 | 1.8609 | 0.0286* | −0.2471 |
| 90 | 5 | 0.9514 | 1.7771 | −0.0156* | −0.3309 |

* Under the 5 cm of error requirement.

corrupted by variations in the ground, holes, debris, or even small plants growing in the field.

Intuitively, the parameters match the physical aspects of the outdoor field. The top layers of leaves form a dense canopy, with only a few protrusions by leaves and corn tassels. Only a small number of measurements in each scan will reflect from these surfaces, which means $p_c$ can be very small. On the other hand, the ground readings fluctuate because of furrows and uneven ground. This requires more noise rejection from the ground estimate, results in $p_g = 0.95$. Given that the corn was mature and in good health, the canopy in the field is representative of the highly cluttered environments the UAS will operate in. Future studies will examine the impact of different fields on this parameterization; however, we are encouraged by the fact that similar parameters yield good results in both our indoor and outdoor tests. Accurate height control in outdoor environments will enable a wider range of UAS missions, such as collecting physical specimens, using smaller and passive sensors that have a short range, and improving the spatial data resolution.

## Designing and Operating UASs that Work Close to the Environment

During the course of developing systems that interact closely with the world, including the two systems described in the case studies, we found some general principles for designing and operating UASs in close proximity to the environment. These principles include using different sensing modalities for different ranges of altitude, specializing the sensors to meet domain-specific tasks, measuring how flying impacts the datasets collected, and adjusting acceleration and decisive maneuvers depending on the proximity of the environment. In this section, we describe some of these principles and discuss some of the continuing technical and administrative challenges in aerial mobile manipulation.

### Multiple Sensing Modalities

We found it was important to have multiple ways of estimating altitude with different resolutions depending on the proximity of the environment. Typical UASs and manned aircraft rely on air pressure sensor based altimeters that are calibrated based on local atmospheric conditions. These perform well when flying typical altitudes for these vehicles of hundreds or thousands of meters above the ground; however, these altimeters drift multiple meters over a single flight, making them ill-suited for flight extremely close to the environment. The two case studies in this article present methods for estimating height when flying within 1 m of the environment. The water sampler relies on a pair of ultrasonic range finders, a pressure sensor altimeter, and conductivity sensors, while the crop height system relies on a 2D laser scanner and a pressure-sensor altimeter. By integrating these sensors and developing methods to filter and merge data from these sensors, we are able to fly safely and precisely over water and crops where more precise altitude control is required.

### Task-Bound Sensing

We found it was important to specialize the sensors included in our system to fit each particular task. Although an ideal, general-purpose UAS for environmental interaction would include all of the sensors found on our systems plus other sensors [radio detection and ranging (radar), 3D light detection and ranging (LIDAR), RGB-D (RGB-Depth) cameras, Real Time Kinematic (RTK) GPS, etc.], in practice, UASs have extremely limited payloads, and even if a UAS could carry more sensors, it would be at the cost of decreased flight time. As such, every UAS must be configured for its specific task. In the case of the water sampler, we cannot use a laser scanner as reflection and refraction lead to extremely poor performance of this sensor over water. Further, the laser scanner and processing system weighs over 500 g compared to the less than 15 g for the pair of ultrasonic range finders. For the crop-height estimation, we cannot use ultrasonic sensors as they would, at best, detect just the top of the crops and could not be used to estimate the distance to the ground and therefore crop height. Given that this heavier sensing mechanism is required, we attempt to maximize its usage by using the data it generates for multiple purposes (e.g., characterizing the density of the canopy and the angle of the leaves).

### Understanding UAS Side-Effects

To characterize how flying impacts the datasets and samples we collect, we also performed experiments to verify that water properties and crop-height measurements correlated with datasets obtained by traditional techniques. These preliminary experiments show these systems work, but before these can be used widely by scientific, agricultural, and policy users, we must conduct further experiments to calibrate the sensors and verify the results' variation against an agreed baseline. Precisely calibrating sensors is always a challenge and doing so on flying platforms can be even more difficult due to factors such as stirred up dust from close flight, vibrations from flight, high-frequency noise in the power systems from the motors, compensating for vehicle pitch/roll/yaw, and atmospheric impacts (lighting, temperature, air pressure). While there is an increasingly large number of lightweight sensors for UAS use, there will be other parameters that need to be taken into account when flying with these sensors and calibration needs to be done in flight.

### Adjusting Navigation and Operating Parameters

We found it was useful to change the behavior of the system to limit sudden movements and accelerations when near the environment. We did this by changing controller parameters dynamically so that the systems behaved more cautiously when near obstacles. Although the systems are capable of making decisive maneuvers even when close to the ground, the human backup pilots felt more comfortable when working with a system that moves more gently, in part because they can more easily identify when the system is correctly sensing the proximity to the environment.

One technical challenge that remains prevalent is to obtain more precise and reliable localization data. In our case studies, we focused on estimating height above the environment. For position, we relied on GPS. GPS works in large, wide-open environments, but with obstacles interspersed in the operational area, more precision may be needed. RTK GPS can provide significantly better position and altitude information, although at this time most of these units are too heavy for the micro-UASs we use for close interaction with the environment, and they also require significant setup and base stations. RTK GPS may work well for many applications; however, if the environment is dynamic (e.g., if animals, people, or other vehicles are present) or if the operator is not close enough to see fixed obstacles (e.g., power lines or tree branches), then it is important to continuously monitor the environment and react to these types of obstacles. In the future, detecting and avoiding these types of obstacles will likely require additional sensors such as radar, 3D LIDAR, RGB-D cameras, or other sensors that give situational awareness. As with all UASs, there will be a tradeoff between adding potentially heavy sensors to improve automated obstacle avoidance and overall flight time.

There are a number of other technical challenges in addition to making sure UASs interacting with the environment do not collide with obstacles, as we discussed in the "Recent Advances in UAS-Environmental Interaction" section. Additional challenges include dealing with the flight and contact dynamics involved when a flying vehicle comes in contact with something in the environment and creating systems that are easy for non-expert users. Another limiting factor of many of the micro and even larger UASs is the limited payload and flight time. There are also challenges related to ease of use since many of the scientists and professionals that want to use UASs are not expert operators. In addition, with the plethora of new UASs available on the consumer market, there is a lack of information on the reliability and failure modes of these systems.

Beyond the technical challenges associated with bringing UASs close into the environment, there are other non-technical issues that must be addressed. In the US, the FAA has proposed new rules for integrating UASs into the national airspace, but these will take time before they are fully implemented. Right now it is possible for state agencies to obtain COAs, and some commercial companies have received permission to fly UASs with a Section 333 Exemption, but the process is non-standard and sometimes limiting. Further, even when the rules are fully implemented, they will likely not address all use cases and configurations of UASs as the technology is rapidly advancing. How to best integrate UASs as the technology quickly evolves is an ongoing debate; however, reason would dictate that UASs that are 2–3 kg and flying within a few meters of the ground should be easiest to safely fly with existing air traffic. We are, therefore, hopeful that upcoming regulations will not restrict, but rather enable, novel uses of UASs that can interact with the environment to aid scientists and practitioners.

## Conclusions

UASs have the potential to transform the way that scientists and practitioners collect data and samples, particularly by flying low and directly interacting with the environment.

The increased spatiotemporal resolution of these datasets will enable policy makers to better measure the impact of stewardship practices and policies. In this article, we presented two case studies of low flying micro-UASs that interact with the environment. In the first, an aerial water sampler autonomously navigates to remote or hard-to-access bodies of water to automatically retrieve samples. In the second, a low-altitude crop surveying UAS flies extremely close to the crops to extract physical properties such as crop height that cannot be easily measured remotely. For both cases, we discussed the sensors and methods we use to fly safely very close to the environment. In preliminary experiments, we validated that water properties measured by these novel systems correlate with water properties measured by traditional sampling techniques. In the future, we plan to conduct a more detailed analysis and comparison of UAS and traditional sampling methods. The case studies presented here are only two examples from the growing body of work in aerial mobile manipulation and proximal sensing. These advances, plus the continuing miniaturization and mass-production of sensors and actuators, indicate that the next generation of UASs will do far more than sense from afar.

## Acknowledgments

We would like to thank our limnologist and environmental engineering partners at U.C. Berkeley, Dr. Michael Hamilton and Dr. Sally Thompson, for their continuous support of these efforts. The authors would like to thank Baoliang Zhao for his water sampler chassis design and Jon Luetchens and Collin Lamkey for their assistance in collecting ground truth data in the corn plots. This work was also greatly assisted by Craig Allen, Allison Zach, Hengle Jiang, Adam Taylor, Michaella Chung, James Higgins, Christian Laney, Jacob Greenwood, Christa Webber, Emily Waring, Seth McNeill, Jared Ostdiek, Najeeb W. Najeeb, Daniel Rogge and the NIMBUS Lab. Finally, we would like to thank the reviewers of this article and participants of the 2014 Argonne National Labs "Applications of UAS to Land and Natural Resource Management" workshop for their constructive feedback on this research.

## Funding

This work was partially supported by USDA #2013-67021-20947, NSF IIS-1116221, NSF CSR-1217400, NDEQ grant #56-1131, Robert B. Daugherty Water for Food Institute 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.

## Notes

1 Maxbotix MB1240-EZ4 ultrasonic rangers (Maxbotix, 2014).

2 For DO and temperature, a single reading was obtained with the hand sensor at the location; but for the UAS mechanism, it was tested on each of the three samples.

3 Lab measurements use a Dionex Ion Chromatograph AS14A, made by ThermoFisher.

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Submitted February 14, 2015; revised April 8, 2015; accepted April 15, 2015