Experiences with Autonomous Sampling of Pit Lakes in North America using Drone Aircraft and Drone Boats

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Abstract

Autonomous drones have created opportunities for pit lake monitoring. This paper reviews two water sampling programs conducted on pit lakes in North America since 2017 using unmanned aircraft and boats. The Canadian-based engineering firm Hatch connected an off-the-shelf unmanned aerial vehicle (UAV) to a commercial sample bottle and collected samples as deep as 80 m from seven pit lakes. Montana Tech used a custom-built drone boat to measure physiochemical profiles and sample the Berkeley Pit. These examples highlight the potential for drones to collect high-frequency, vertically-distributed data from pit lakes, minimize human health risks, and improve pit lake management.

Keywords: pit lakes, UAV, UAS, ASV, drones, sampling, geochemistry, water quality

Introduction

On a global scale, 70% of the properties owned by the six largest mining companies exist in water stressed regions (Beck, 2018). Open pit mining in these regions will often result in the formation of mine pit lakes following mine closure (Castendyk and Eary, 2009). Given the present value of water in these regions, post-closure pit lake water quality is highly scrutinized by companies, regulators, and the public. Management of pit lake water quality requires frequent water sampling at multiple depths to assess the accuracy of predictive models, maximize post-mining re-use, mitigate poor water quality, comply with regulatory requirements, and ideally, receive bond return and release from liability. To facilitate best management practices, regulators in the State of Nevada, USA, require pit lakes with maximum depths greater than 8 m deep to be routinely sampled at multiple depths.

However, pit lakes present high health and safety risks for human water samplers. Fatal risks include drowning, hypothermia, rock falls, landslides, tsunami, fall from heights, and asphyxiation from water degassing. These risks are compounded by limited communication, remoteness of sites, and minimal access for emergency response crews. In some cases, these risks combined with the expense of risk mitigation have been used to justify an indefinite postponement of sampling. The resulting data gaps limit stakeholder knowledge on the state of the pit lake, the ability to verify numerical predictions, and ability to pro-actively manage water quality.

Recent technological advances have made it financially feasible to obtain an off-the-shelf unmanned aerial vehicle (UAV, or drone aircraft) with an advanced flight controller and suitable payload capacity capable of performing routine water sampling at mine sites, and thereby, significantly reduce the risks and costs of pit lake sampling. Since 2013, researchers have used UAV's to collect surface water samples from ponds and lakes (Ore et al. 2015). Castendyk et al. (2017a) collected deep water samples and measured *in situ* physiochemical profiles from a pit lake and a drinking water reservoir using a drone aircraft. This was the first published application of a UAV completing pit lake water sampling at depth.

Elsewhere, advances in communications technology have led to autonomous surface vehicles (ASV; or drone boats) capable of measuring water quality properties (Dunbabin et al. 2009). Duaime et al. (2018) report on a custom-built drone boat which has repeatedly collected samples and measured *in situ* physiochemical profiles from the Berkeley Pit in Butte, Montana, USA.

This paper synthesizes the works of Castendyk et al. (2017a) and Duaime et al. (2018) plus experience from recent sampling events, in order to assess the state-of-the-art of drone water sampling of pit lakes in North America. We identify the successes and challenges facing both programs and define the steps needed for industry-wide adoption of drone sampling techniques. We anticipate that the adoption of drone sampling programs will improve safety, lower costs, produce more data, and ultimately, improve pit lake management.

The Hatch Drone Aircraft

Design and Operations: In 2016, the Chinese UAV manufacturer DJI released the *Matrice 600* hexacopter for $4,500 USD. With the ability to lift a payload of 6 kg, this drone aircraft made it possible to transport items other than cameras for a considerably lower cost than existing commercial UAV's with equivalent lift capacity. Researchers at Hatch Associates Consultants in Denver, Colorado developed an attachment for the *Matrice 600* which connected the UAV to a 1.2-L Niskin water bottle sold by General Oceanographics in Florida, USA (Castendyk et al. 2017b). This patent-pending attachment enabled the drone to transport the sample bottle at the end of a 100-m static tether (Figure 1). In operation, the drone would lower the sample bottle to the desired sample depth, an independent remote-control would release a 0.9 kg messenger suspended below the drone, the messenger would travel down the tether and close the sample bottle, and the drone would rise and return to the staging area.

Prior to water sampling, the tether was connected to a YSI *CastAway* conductivity, temperature, depth probe (CTD). This lightweight sonde was lowered through the full extent of the water column and measured *in situ* temperature, electrical conductivity and water density as a function of depth at 5 times per second during both the decent and accent. Upon retrieval, these data profiles were immediately uploaded to a laptop computer via Bluetooth connection. These data served two important purposes: (1) sounding the lake to find the surface location corresponding to the deepest point in the lake, and (2) defining the depths of internal layers and boundaries (e.g. epilimnion, thermocline, hypolimnion, chemocline, monimolimnion) from which sample depths were targeted.

Two independent methods were used to measure the depth of a water sample. During flights, the drone pilot positioned the Niskin bottle on the water surface and noted the drone's elevation, called the "baseline." The target sample depth was subtracted from baseline to determine the sample elevation. The drone was lowered to the sample elevation and the sample was collected. The *Matrice 600* has an altitude error of +/- 50 cm which became the initial depth error. In addition, a small pressure transducer (Van Essen, *Micro-Diver, DI610*) with a depth error of +/- 10 cm at 100 m of water pressure was connected to the mid-point of the sample bottle which allowed the actual depth of the bottle to be verified during post-flight processing. This approach potentially yields greater depth certainty than traditional boat-based methods which typically do not use a pressure transducer.

Achievements: To date, the Hatch drone aircraft has sampled two pit lakes in Ontario, Canada, and five pit lakes in Nevada, USA (Table 1). The system has measured multiple *in situ* profiles of temperature, electrical conductivity and water density from each pit lake, and has collected water samples from multiple depths with a maximum record of 80 m deep in the Pamour Pit at the Porcupine Gold Mines in Timmins, Ontario. To the best of our knowledge, this is the deepest water sample ever collected with a UAV. These flights demonstrated the ability of the system to consistently collect water samples at depth from pit lakes lacking safe shoreline access. The Nevada Department of Environmental Protection (NDEP) observed the system in operation in August 2017 and reported "The methodology is acceptable for regulatory purposes and allows for multiple samples to be collected while maintaining human and environmental safety" (Newman et al., 2017).

Limitations and Challenges: Limitations of the Hatch drone aircraft include the following: (1) The maximum sampling and profil-

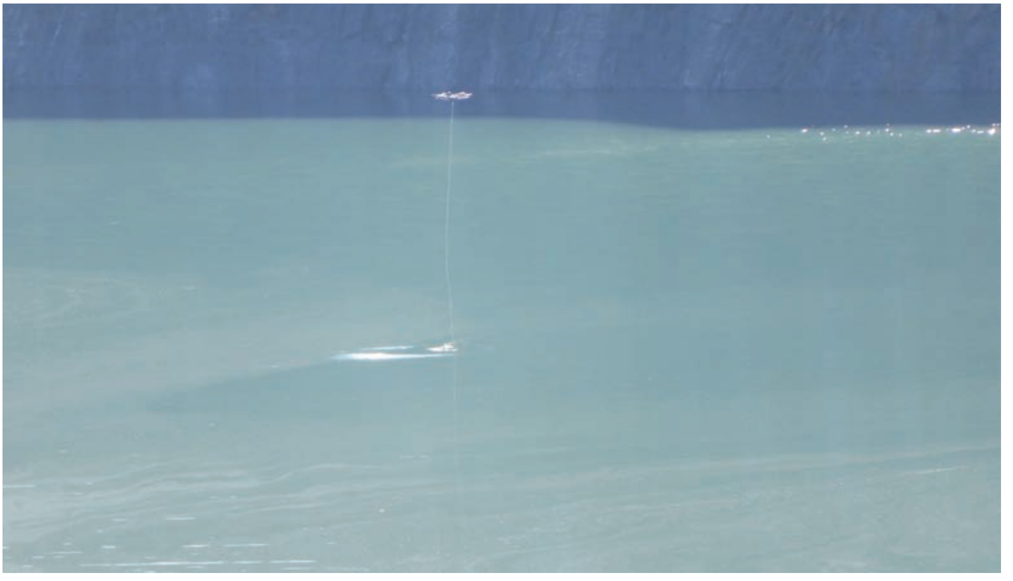

Figure 1 The Hatch drone aircraft sampling Pamour Pit, Ontario, Canada, June 2017

Table 1 North American pit lakes sampled by the Hatch drone aircraft

Name	Location	Owner	Depths (m)	Date
Pamour	Ontario, CAN	Goldcorp	3, 15, 80	6 June 2017
Owl Creek	Ontario, CAN	Goldcorp	0, 8, 18	6 June 2017
Boss	Nevada, USA	BLM*	0	30 July 2017
Manhattan West	Nevada, USA	Kinross	0, 12	31 July 2017
Clipper	Nevada, USA	BLM*	0, 7, 30	1 August 2017
Big Ledge	Nevada, USA	NOV	0, 10, 13	2 August 2017
Dexter	Nevada, USA	BLM*	0, 7, 15	3 August 2017

*US Bureau of Land Management, Nevada

ing depth is ≈100 m because the maximum height for commercial drone operations in the USA and Canada is 122 m (without special permission); (2) The tether can become snagged on trees or powerlines; (3) The sampling bottle can pendulum below the drone making landing the payload difficult; (4) The weight of the payload limits flight duration to < 15 minutes which negates the use of multiparameter sondes that need ≈2 minutes to stabilize readings at each depth; and (6) Moderate winds and light rain can delay or cancel drone operations.

The Montana Tech Drone Boat

Background: The world-famous Berkeley Pit in Butte, Montana, USA, is another example a hazardous environment for water sampling (Tucci and Gammons, 2015). The circular lake is over 1.6 km in diameter, approximately 370 m deep, and stores about 180 billion litres of water. The US Environmental Protection Agency (EPA) and Montana Department of Environmental Quality (MDEQ) have required semi-annual profiling and sampling of the Berkeley Pit as part of monitoring for the Butte Mine Flooding Operable Unit of the Silver Bow Creek Superfund Site. This sampling was performed manually with a field crew using a boat and traditional sampling methods. By 2013, the pH of the pit lake ranged from 2.5 to 3.0 (PitWatch, 2013). In 1998, a significant slope failure occurred on the south east rim that caused 15 m waves to propagate across the lake. More recently (2012-2013), a number of smaller wall-rock failures made pit managers concerned that a wave could capsize the sample boat and slam the occupants into the pit walls, resulting in drowning or hypothermia. Due to these health and safety risks, sampling and profiling operations temporarily ceased in 2013.

Design: In 2015, Montana Tech of the University of Montana in Butte, Montana, USA, was commissioned by Montana Resources and the Atlantic Richfield Company (a subsidiary of British Petroleum) to develop a remotely operated, semi-autonomous, drone boat to profile and sample the upper 200 m of the Berkeley Pit. The design had to consider the caustic nature of the water, telecommunication over a large water body, and management of hoses and reels.

The physical platform was built around a 4-m-long, flat-bottomed, drift boat (Duaime et al., 2018). Two electric trolling motors were mounted in fixed orientation on opposite sides of the boat. Each motor was controlled independently for skid-steer navigation. The boat itself was made of fiberglass and very resistant to the caustic water within the Berkeley Pit. The fiberglass body made an ideal platform for mounting hardware and transporting necessary equipment (Figure 2).

Central control of the boat was built around a Raspberry *Pi* computer. The Raspberry *Pi* controlled several custom printed circuit boards with their accompanying microcontroller to control the data reel, the hose reel, the sampling mechanism, the pumping and various other systems. The two primary tasks were profiling and sampling, but also of interest were auto-pilot and communication.

Profiling the water was performed using a Hydrolab *MS5* data sonde. The data sonde was able to measure depth, temperature, pH, electrical conductivity, dissolved oxygen, and turbidity. The sonde comes with a manually-reeled data cable of 200 m length which had to be motorized to be operated remotely. The reel was also modified to have a bump-stop to sense when the sonde had reeled all the way in, click counters to determine the approximate depth, and a linear stage to raster the cable evenly across the reel. The data from the sonde was able to be logged directly to the Rasperry *Pi* computer during descent and ascent through the water column. As with the CTD used in the Hatch system, sonde data aided the targeting sample depths.

Sampling the water was performed using a 228-m-long vinyl hose on a motorized reel. The reel was further modified to have a traveller to raster the hose evenly across the reel. Like the data sonde reel, the hose reel used a click counter and bump stop to manage the length of the hose in the water. It also had a mechanized outrigger to hold the hose below the level of the electric props during sampling and to raise the hose above the level of the water for navigation purposes. To prevent the weight of the hose alone from unravelling the hose, a brake was added to the reel.

An ISCO *3700* sampler was used to pump water from the lake and to store samples in twenty four, 1-L polypropylene bottles. The ISCO *3700* sampler was reverse engineered to be remotely controlled. An additional pump was used to prime the hose to ensure that no air pockets existed within the hose and to purge the volume of the hose between samples. Due to the negative pressure pumping and length of the hose, a single purge volume of the hose took 20 minutes.

Communications were achieved using two different pathways: a 2.4 GHz wifi link using high-gain antennas, and a standard radio control utilizing 433 MHz. The wifi link was able to flawlessly achieve high bandwidth communications at over 4.8 km on water. This allowed for control of the many systems, video and audio feedback, and direct data feedback from the instruments. The 433 MHz radio had to have a modified base station antenna to eliminate picket fence interference (i.e. constructive interference) due to the proximity of the boat's receiver to water. This radio controlled the autopilot as well as the locomotion of the boat.

Video feedback was relayed through the wifi link. These provided feedback with relatively high latency of 500-1500 ms as well as the ability to pan and tilt the cameras. The accompanying audio was an important feedback mechanism for the operator helping to determine when motors were working and whether a command had been completed. A lower latency camera (130 ms) was added for ease of navigation though it was on a fixed view.

Figure 2 *The Montana Tech drone boat prior to deployment in the Berkeley Pit, Butte, Montana, USA*

Achievements: Between its first deployment in May 2017 and May 2018, the drone boat had completed six successful profiling and sampling trips. A comparison of physiochemical profiles collected between May 2017, October 2017, November 2017, and May 2018 show that average pH rose from 3.7 to 4.2, and that the lake was oxygenated and fully mixed to a depth of 200 m (Montana Bureau of Mines and Geology, unpublished data). Not only has the drone boat allowed data collection to safely resume, the results dramatically reshaped the geochemical conceptual model of the Berkeley Pit, demonstrated the potential to improve the water quality of very acidic pit lakes, and underscored the importance of high-frequency profiling and sampling in pit lakes. The drone boat was actively being used to collect data at the time of writing.

Limitations and Challenges: The principle limitations of the Montana Tech drone boat are: (1) the need to maintain a stable, obstacle-free, access road leading to the pit lake shoreline; (2) the need for humans to drive inside the pit perimeter and manually deploy the boat; (3) the maximum profiling and sampling depth of the boat is 200 m whereas the maximum depth of the Berkeley Pit is close to 370 m, meaning the lower 170 m of the lake is not studied by the system; and (4) with a price tag of close to $80,000 USD, reproduction of the drone boat for use at other pit lakes may be cost prohibitive. Several challenges, such as picket fence interference and hose line management, created initial difficulties which were surmounted over the course of the project.

Comparison of Methods

The examples presented herein demonstrate the potential for drone water sampling methods to replace traditional water sampling methods in pit lakes. This shift is likely to improve safety, reduce costs, increase data collection, and improve pit lake management. Both systems initially collect profiles of physiochemical parameters throughout the water column, and use these profiles to select appropriate sample depths.

The main advantages of the Hatch drone aircraft are the transportability from pit lake to pit lake and the ability to sample pit lakes that lack any safe access to the water surface. The disadvantages are the short flight times (< 15 minutes), the limited sample depth (< 100 m), and potential air space restrictions. In contrast, the main advantages of the Montana Tech drone boat are the considerable depth of sampling (> 200 m), the profiling of additional physiochemical parameters, and the ability to collect two dozen water samples in a single voyage. The disadvantages include the need for a safe, stable access road and for humans to drive the drone boat to the lake shoreline, plus the high cost. Both systems operate best under calm winds, flat water, and no rain.

Both drones fill sampling niches and are likely to be utilized in the future. Mining companies that anticipate developing low-water-quality, deep pit lakes that will require routine sampling long into the future may consider building a dedicated drone boat. This will ensure frequent water sampling provided there is continuous access to the shoreline. Mining companies looking to survey existing pit lakes on their properties may wish to initially employ a drone aircraft.

Steps Needed for the Adoption of Drone Water Sampling

The following non-technical issues need to be investigated before the mining industry widely embraces drone water sampling: (1) Mining companies need to quantify the costs and safety risks associated with boat-based sampling and compare these against drone sampling; (2) Regulators need to accept water samples collected by drones for compliance monitoring; (3) Mining companies need to review insurance and liability requirements for drone pilots to ensure that the level of required financial assurance is consistent with the degree of risk; (4) Government agencies overseeing commercial drone activities need to clarify requirements for commercial drone pilots and advance beyond line-of-site operations; (5) Consultancies need to train commercial drone pilots consistent with local government regulations; and (6) Mining companies need to sign non-disclosure agreements to protect the intellectual property rights of drone innovators.

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