INTERNATIONAL JOURNAL OF MINING, RECLAMATION AND ENVIRONMENT
https://doi.org/10.1080/17480930.2018.1549526

Development of a UAV-mounted system for remotely collecting mine water samples

Bikram Pratap Banerjee[a], Simit Raval[a], Thomas J Maslin[a] and Wendy Timms[b]

[a]Australian Centre for Sustainable Mining Practices, School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney, Australia; [b]School of Engineering, Deakin University, Waurn Ponds, Australia

ABSTRACT

Accurate and frequent measurement of mine water quality is essential for timely management and regulatory requirements. At mines, traditional water sample collection practices are sometimes unsafe or impractical due to accessibility challenges. Unmanned aerial vehicle (UAV)-based remote water sampling has benefits in accessing small, shallow and isolated waterbodies in hazardous environments. In this study, an integrated electromechanical pneumatic system was developed to provide an effective, efficient and safer means to acquire mine water samples using UAVs. The system was tested to collect and analyse ponded water from a tailings storage facility to measure pH, electrical conductivity and dissolved oxygen.

ARTICLE HISTORY
Received 4 March 2018
Accepted 14 November 2018

KEYWORDS
Mine water quality; mine tailings; remote water sampling; UAVs

1. Introduction

Poor quality water from mining operations can include saline discharges [1,2], acid mine drainage [3] and ponded water and leach water from tailings, all of which can degrade freshwater resources and potentially impact sensitive environments and ecosystems [4]. Poor water quality may involve one or more of the following parameters: salinity, turbidity, acidity, metals, organics and other contaminants of concern such as toxic algae or radiological elements. The concentration of dissolved oxygen (DO) may also be an indicator of water that is suitable for aquatic ecosystems, while water with low DO, low pH (i.e. acid) and high total dissolved solids (TDS) would be considered poor quality. Salinity or total salts can be analysed from laboratory tests of water samples, or estimated on site with an electrical conductivity (EC) sonde. Site-specific water quality values that are suitable for water reuse on site, permissible for discharge or acceptable for environmental purposes would be determined by local authorities and guidelines [1]. Accurate monitoring of the mine water quality parameters is therefore an essential requirement for managing mines. Existing practices for mine water quality measurement can be hazardous, expensive and impractical.

In recent years, the technological capabilities of drones or unmanned aerial vehicles (UAVs) have substantially increased, leading to increased utility in environmental monitoring applications [5–8]. The term UAV refers to an aerial platform that does not need an on-board pilot [9]. Therefore, UAV systems eliminate the potential risk to a human pilot and improve accessibility to difficult and dangerous terrain. UAV-based water sampling systems have already been used to collect surface water from freshwater sources [10] and wetlands [11]. For mining operations, a UAV-based water

CONTACT Simit Raval simit@unsw.edu.au

quality sampling system opens many opportunities and applications to improve the effectiveness and safety of monitoring practices to improve environmental outcomes.

The objective of this study was to develop a low-cost UAV-based water sampling system to enable risk-free mine water inspections. Firstly, different existing water sampling techniques, including surface water vehicles and UAVs, were identified and evaluated. Secondly, a cost-effective integrated electromechanical pneumatic system (IEPS) for UAV-based water sampling was designed and tested in laboratory conditions. Finally, the system was applied in a real-world scenario to collect ponded mine waste water from a tailings storage facility (TSF).

2. Existing techniques and designs

Existing methods for water sampling can be broadly classified into three groups: traditional approaches, surface water vehicles and recent UAV-based methods.

2.1. Traditional water sampling techniques

Current protocols for in situ water sampling [12] in the mining industry largely use traditional water sampling techniques, which primarily include manual collection (or grab sampling) of water samples directly into an appropriate storage container such as a bottle. However, intermediate containers such as buckets, beakers, pumps, filters, syringes, sediment grabs, trowels and/or sampling rods are sometimes necessary to assist the sample collection process [12]. Grab sampling is often carried out on difficult and dangerous terrain. Moreover, accessibility remains limited to near the shore of the water source. Automatic devices such as refrigerated or non-refrigerated automatic pump samplers are sometimes used to collect samples at a periodic interval or at required preset conditions (temperature, turbidity, water level) [12]. However, programmable samplers are static units that limit the sampling extent, and installation of a wide area network of programmable samplers is expensive.

2.2. Surface water vehicles

Manual or autonomous controlled surface water vehicles provide mobile solutions for water sampling. These systems generally include a vehicle-mounted sample acquisition unit to acquire physical samples, or profiling sensors to measure water quality parameters electronically on a memory device. Dunbabin et al. [13] developed an autonomous surface vehicle (ASV) capable of navigating in complex inland water areas to measure a range of water quality properties and greenhouse gas emissions. The autonomous system was integrated using a 5-m floating vessel with on-board sensor networks for remote operation, data transfer and adaptive sampling. The profiling sensor could be used between a water depth of 5.5 and 20 m at a sampling speed of 0.5–3.0 ms^{-1}. The work emphasised the ability of the ASV to complement existing monitoring campaigns enabling spatial and temporal monitoring over hundreds of kilometres. Fornai et al. [14] identified the challenges in obtaining water samples at variable depths using ASVs and designed a specialised sampling probe to collect up to five water samples from selected depths into a winch system for later analysis in the laboratory.

Although surface water vehicles are functionally superior to traditional sampling methods and have been used in a range of water systems such as lakes and wetlands, their use in a mining environment is often difficult. Mine water can be highly corrosive due to its chemical composition which can cause damage to the vehicle or reduce its lifetime. Water in TSFs can often dry out and exist at a shallow level in disconnected ponds which can limit the ability of the surface vehicle to float and reach isolated ponds.

2.3. UAV-based water sampling

UAVs are more appropriate platforms than ASVs to access small, shallow and isolated water-bodies. Schwarzbach et al. [11] used a helicopter-type UAV to collect water samples from a natural wetland by hovering close to the water surface. Samples were collected through a 1.5 m tube into a single storage reservoir (500 mL) using a miniaturised pump. The work describes the robustness of the system under external influences such as wind gusts and load changes (as water is pumped in) during flight. The positional accuracy in hovering mode provides less than 10 cm of drift in all directions. The integration of an autonomous flight system with fully functioning remote sensors was identified as the best research direction. Ore et al. [10] devised an autonomous aerial water sampling mechanism using an on-board miniaturised pump to obtain three samples (up to 25 mL each) from a flying mission of 20 min using a quadcopter-UAV. Ancillary sensors and algorithms were implemented for altitude approximation and vehicle control over the water surface. The quadcopter was navigated to the global positioning system (GPS) location of the sampling point using an on-the-shore ground control station. Temperature, DO, sulphate and chloride ion concentration measurements for the samples collected from the UAV were consistent with the sample collected by hand [10].

3. Technical approach

The selection of a suitable design and mechanism for a UAV-based water sampling system was based on the following requirements.

3.1. Light weight

The payload capacity of currently available UAVs is often a limiting factor due to maximum-take-off-weight and aviation regulations. Therefore, the weight of the designed water sampling system was kept minimal (~ 1.5 kg) to ensure its fit with a range of different UAV platforms. A lightweight unit also preserves the natural flying characteristics and safety standards of the UAV, with minimal loss of the UAV’s endurance. Different civil aviation regulatory authorities (such as Civil Aviation Safety Authority, Australia) have strict restrictions on the total flying weight of a UAV.

3.2. Operational simplicity

It is essential in the planning phase to consider the operational ease of the final product. The water sampling system has been designed for ease of operation with simple-to-follow instructions and protocols. Operational simplicity was met by considering in-field ergonomics to ensure a simple, reliable and efficient mode of operation for the end users in the mining industry.

3.3. Chemical inertness

It is important to use appropriate material(s) to collect and store water samples that do not influence the chemical characteristics of the water samples. Teflon tubes were used due to its chemical inertness. The material does not absorb metals and organics over time.

3.4. Low cost

The most challenging constraint was to design a low-cost sampling system to enable wider adoption of the developed technology with a range of existing UAV systems for water quality monitoring requirements.

3.5. Electromechanical pneumatic system

A basic syringe-based pneumatic system was devised to collect and store water samples with the mechanical motion produced from an electric servo motor (Figure 1). A 25 mL pneumatic syringe was used to draw fluid in (or out) by means of a low (or high) pressure created inside the barrel with the outward (or inward) movement of the plunger. The lateral movement of the plunger was regulated with an electromechanical motion of a servo arm attached to the plunger end. Once stimulated by a trigger signal from the transmitter (Tx) to the receiver (Rx), the servo arm is rotated by 90° causing a 20 mm lateral movement of the plunger. A narrow Teflon tube of inner diameter (d) of 5 mm and 2.5 m in length was attached to the mouth of the pneumatic syringe to collect water samples. The open end of the Teflon tube was sealed with a polystyrene filter net to prevent large particles (not TDS) from flowing in and clogging the mechanism during sample collection. With a suction volume of V = 25 mL or 25 cc produced by the pneumatic syringe barrel, water flows to an approximate height of $h = 4 \times V/\pi d^2 = 1.27$ m into the Teflon tube, i.e. the water sample never reaches the pneumatic syringe barrel. This is not an issue since the sample is retained within the Teflon tube and the suction pressure generated by the electromechanical pneumatic system (EPS) prevents the fluid from flowing out. An advantage of the fluid remaining within the Teflon tube and not in the pneumatic syringe is that it reduces the risk of cross-contamination.

An individual EPS is able to collect up to 25 mL of water from a specific location. Ideally a large number of EPSs would be more able to collect samples from multiple locations during a single UAV mission. However, practical challenges such as overall weight, size and power supply requirement limit the number of EPSs on a UAV. Considering these practical constraints, a total of six EPSs were used to form a hexagonal-shaped construct of an IEPS (Figure 2). The simple design of the EPS made the final unit (IEPS) lightweight and low cost and stored each collected sample in isolation. The power supply unit and the remote trigger trans-receiver circuit were encapsulated inside the hexagonal construct to minimise wire clutter and avoid accidental spillage of water. A downward-looking video transmitting system was also embedded on to the side of the hexagonal construct to monitor the process of water sample collection from the tailings. The overall dimension of the IEPS was modularised to fit beneath the payload bay of a standard quadcopter-type mini-UAV, in this case it was Walkera QR X900. The specification of the IEPS is detailed in Table 1. Figure 2 shows the line diagram and snapshot view of the developed sampling system.

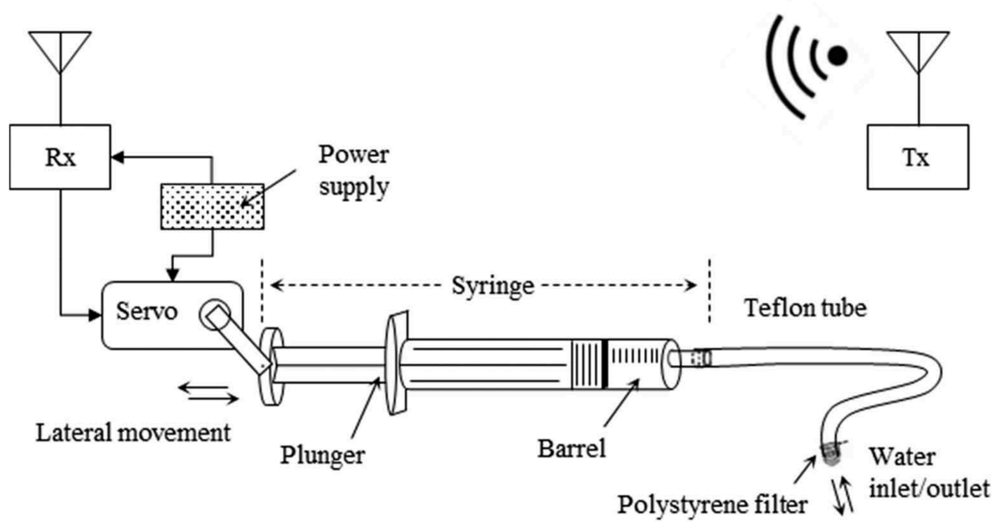

Figure 1. Design and mechanism of operation of the electromechanical pneumatic system (EPS).

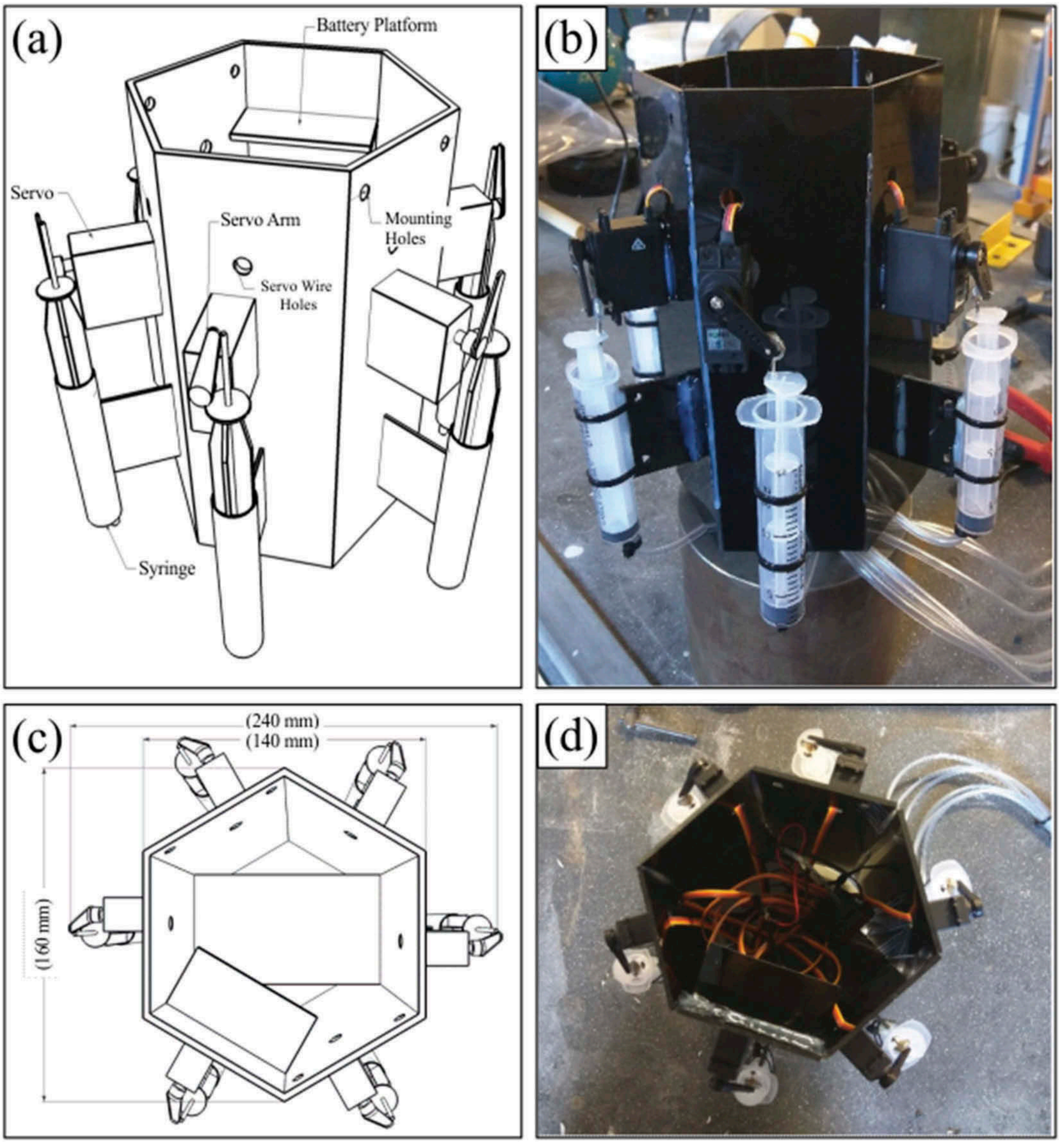

Figure 2. Integrated electromechanical pneumatic system (IEPS): side views (a, b) and plan views (c, d).

Table 1. Specification of the integrated electromechanical pneumatic system (IEPS).

Weight	1.5 kg
Dimensions (L × W × H)	160 × 140 × 240 mm
Number of pneumatic samplers	6
Volume of each pneumatic sampler	25 mL
Required hovering altitude	<2.5 m
Flight endurance	15–20 min

3.6. Laboratory test of measured water quality parameters

Cross-contamination and source contamination of a collected water sample remains a critical concern of any water quality monitoring study [15,16]. Cross-contamination arises from the residual leftovers, such as water and trapped sediment. Earlier design configuration [10,11] addressed the issue of cross-contamination by flushing the storage units with water pumped through the internal pumps. In this design, a standard rinsing mechanism was used: the Teflon tubes were temporarily disconnected from the IEPS and thoroughly rinsed with milli-Q pure water between samples. Since the pneumatic syringe did not come in physical contact with the sample, it was not necessary to rinse it.

Source contamination can arise from the materials that come in direct contact with the collected sample during the acquisition process. Use of chemically inert components such as Teflon tubes and a polystyrene filter easily eliminates the risk of source contaminations. The chemical inertness of the IEPS was analysed using a laboratory test. A total of six reference solutions were prepared for each of the six EPS units in the IEPS. The water quality parameters such as pH, DO and EC were measured using a calibrated portable water quality meter (Hach Company) and sondes. The six reference solutions were collected using each of the six EPS units, and three water quality parameters (pH, DO and EC) were measured to observe any variation from the reference measurements. The comparative analysis of the laboratory test measurements is shown in Figure 3.

The minor variations observed between the EPS measurements and the reference (Figure 3) were within acceptable limits. The first reading in the comparative analysis of pH indicated a higher error, which could have been due to a mis-calibration of the water quality meter upon testing. Ignoring this outlier, the average absolute percentage error was 0.95% for pH, 0.46% for EC and 0.58% for DO. These deviations are extremely small and are within the limits for accurate measurements.

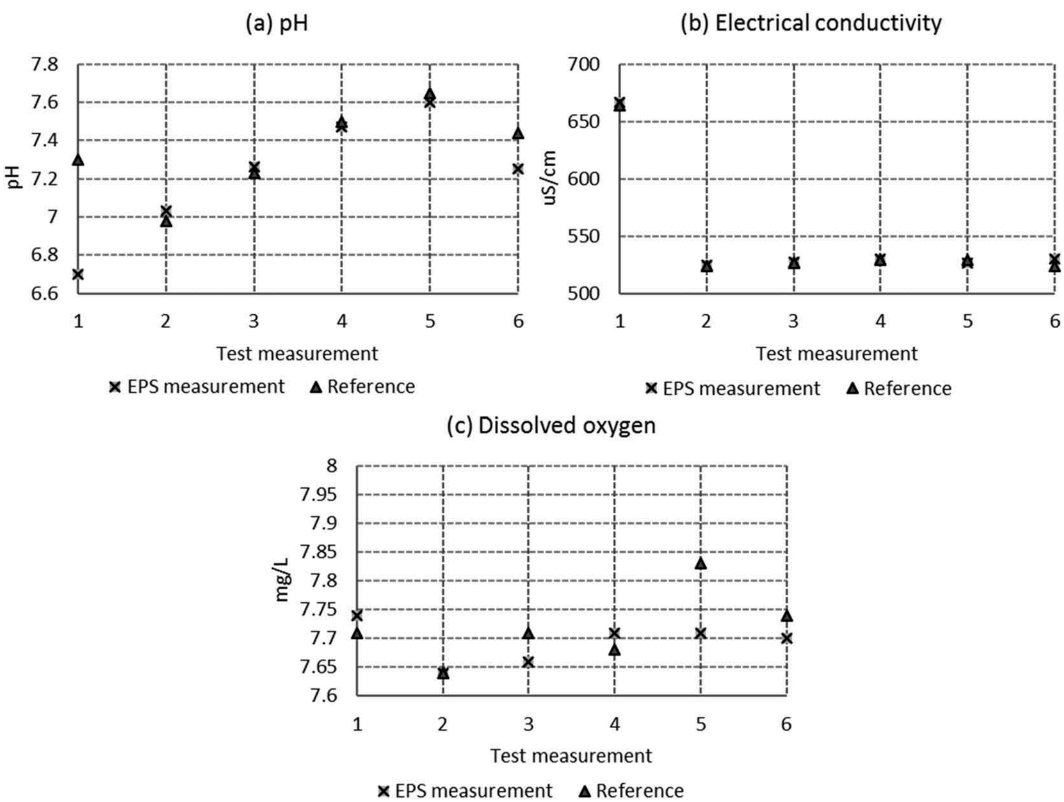

Figure 3. Comparison of EPS measurements against reference solutions for (a) pH, (b) electrical conductivity (EC) and (c) dissolved oxygen (DO).

4. In-flight water sampling experiment in a TSF

TSFs are embankment dams used to store the by-products of mining operations. A TSF is one of the several critical areas where UAV-based water sampling can be very useful. Water in the TSF can originate from the tailings separation and settlement process, or through direct rainfall on the storage area. The hazardous nature of poorly managed TSF water can damage downstream ecosystems including groundwater aquifers through potential leaching and is a threat to wildlife such as birds. Frequent monitoring and appropriate management of TSF water is therefore essential to prevent catastrophic structural failure, damage to downstream ecosystems, contamination of natural water sources and impacts to wildlife [17]. However, monitoring of mine water in TSFs is a safety concern since the water samples are required to be collected physically over the poorly consolidated surface sediments, with potential to be exposed to hazardous mine water. Furthermore, sample acquisition is often not feasible in extremely high-risk scenarios. Therefore, existing water quality sampling practices are limited in terms of spatial extent and frequency over largely inaccessible areas.

An in-field water sampling test with the UAV-IEPS was conducted on a TFS at Glendell Coal Mine in New South Wales, Australia. During the test, the TSF was two unconnected shallow water ponds: a small tailings pond (Figure 4(b)) and a large tailings pond (Figure 4(c)). However, during heavy rainfall the entire TSF would fill and the water level would reach the top of the surrounding wall structure. The bottom of the tailing is comprised of coal sediments discharged from the processing plant, which creates a large muddy area surrounding the water surface, created over time from the settling particles making the area inaccessible to collect water samples. To scope the potential of the UAV-IEPS for collection of water samples from the TSF, two UAV flight missions were performed in clear weather conditions with mild winds (<15 km/h), but occasional wind gusts. Figure 4(a) shows the synoptic view of the TSF with the location of the launch and landing pad, flight paths and sampling locations.

For this mission, an octocopter-UAV assembled from off-the-self available parts (Walkera QR-X900) was used. The flight control system (FCS-RX705) is based on Ardupilot Mega. The IEPS was mounted on the payload bay of the UAV (Figure 5(a)), and the control links and the video downlink were established. The UAV-IEPS was operated in GPS-aided manual operating mode (Figure 5(b)). The UAV was manoeuvred to the desired sampling location and lowered to an approximate hover altitude of 2 m from the water surface, with the collecting end of the 2.5-m-long Teflon tubes immersed in the water. The real-time video feed from the on-board nadir looking camera provided additional guidance. At a suitable hovering height, the respective EPS unit was activated using a remote-controlled trigger signal to collect the water sample from the location. The data acquired through the in-field survey included (1) time-tagged readings for collected water samples and (2) positional information (latitude and longitude) logged at 1 s intervals with the on-board GPS.

The water samples were analysed for pH, DO and EC immediately after collection (on-site) using the portable water quality meter (HACH) and calibrated sondes. For geo-spatial analysis, firstly, the sample measurements were coupled with the positional information in a geographic information analysis (GIS) software package (ArcGIS). Finally, the coupled information was used to produce spatial water quality products using natural neighbour interpolation method [18] within the limits of water surfaces. Natural neighbour interpolation uses an inverse distance-weighted average of the known sample measurements to estimate the values at unknown locations.

5. Results and discussion

5.1. Water quality results from the TSF

A total of seven samples were collected from the two separate water ponds on the TSF. Samples 1–3 were collected from the small tailings pond (Figure 6(a)) while samples 4–7 were taken from the large tailings pond (Figure 6(b)). The collected volume of water for each sample differed due to varying depth of the shallow water ponds. The collected volume of water was less in regions where the depth was extremely low (i.e. in the case of samples 1 and 6). This is because the sample collecting end of the Teflon tube when

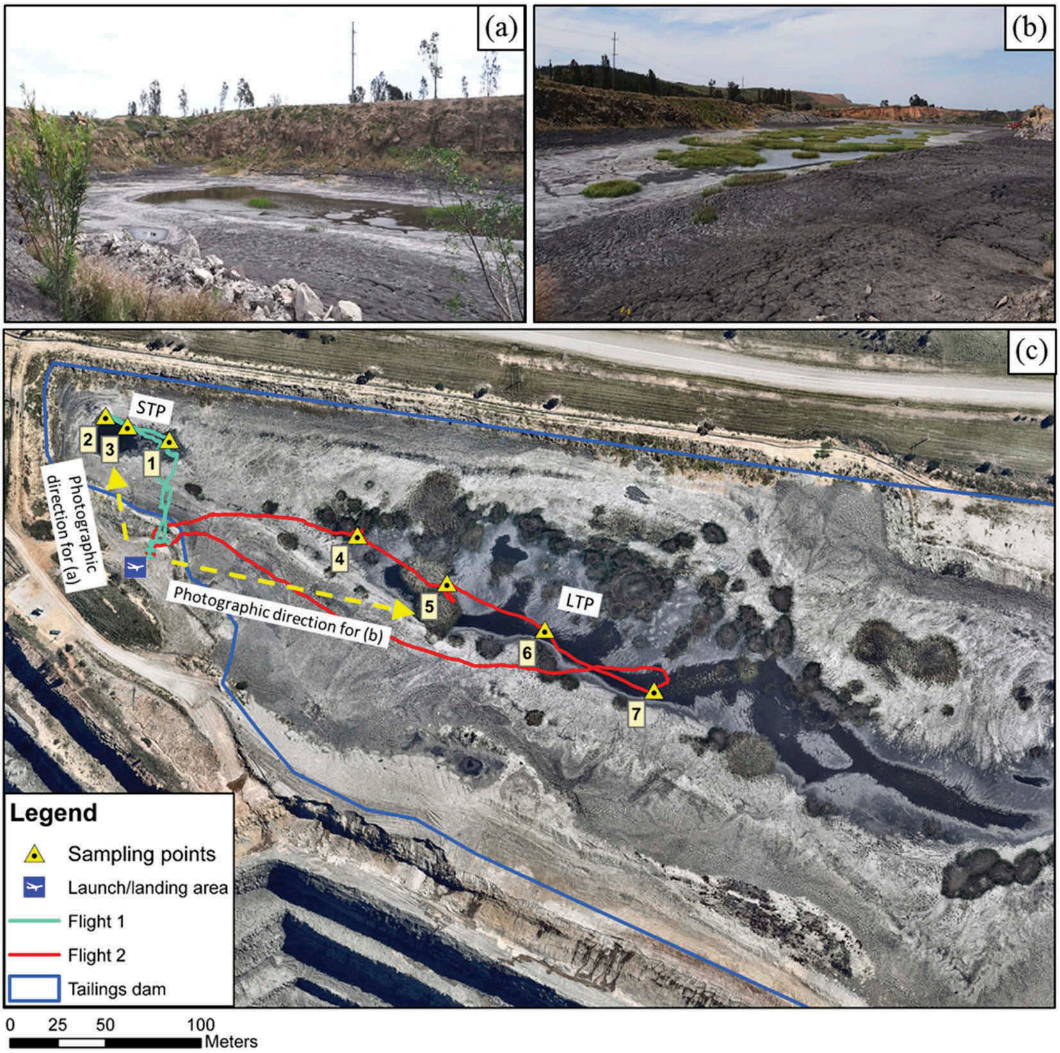

Figure 4. Photographic view of the (a) small tailings pond (STP) and (b) large tailings pond (LTP), and (c) synoptic coverage of the study area with launch/landing area location, UAV flight paths, sampling locations and photographic direction of small and large tailings ponds.

lowered into the shallow water could sometimes touch the pond bottom preventing the pneumatic suction mechanism from collecting more water or coil upwards (above the water surface) after hitting the pond bottom. Nevertheless, the downward-looking real-time video feed was useful to adjust for the required level of immersion to collect sufficient volume of water for analysis. Sample 6 was accidentally dropped during flight due to human error and was not used in further analysis. The fetched samples were tested for pH, EC and DO. The samples collected from the small tailings pond appear turbid compared to samples from the large tailings pond (Figure 6). The measured parameters (pH, EC and DO), time tags and positional information (latitude and longitude) are listed in Table 2.

5.2. Spatial analysis of water quality

The interpolated maps for pH (Figure 7(a)), EC (Figure 7(b)) and DO (Figure 7(c)) depict the spatial profile of the water quality products. These surface water quality products could be used to

Figure 5. Remote water sampling system integrated onto a UAV: (a) on ground and (b) in flight.

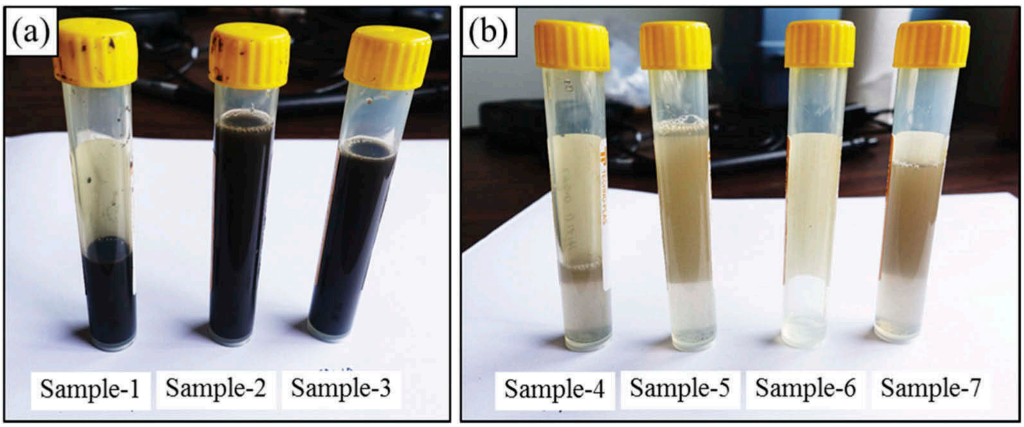

Figure 6. Water samples collected from (a) small tailings pond and (b) large tailings pond through in-flight sampling using UAV-IEPS.

monitor the toxicity level of water and initiate mitigation actions. Overall, the pH levels were found to be consistent between the small and large tailings ponds (Figure 7(a)). The EC was found to be higher in the small tailings pond than the large tailings pond (Figure 7(b)). The significant spatial difference in EC could indicate a number of factors that are important to management of mine water such as leaching, evaporative concentration and a possible source of freshwater inflows. The DO content in the small tailings pond was slightly lower than the large tailings pond (Figure 7(b)). Overall, the water quality was alkaline (average pH = 8.36) and slightly saline, and may require further testing of a wider range of water quality parameters, and possibly passive or active water treatment prior to reuse on site, or possible discharge.

Table 2. Water quality results with sample ID, time tag and coordinate information.

Sample ID	pH	EC (μS/cm)	DO (mg/L)	Time tag (h)	Latitude	Longitude
1	8.18	12.79	6.89	12.04	−32.392881	151.075707
2	8.48	12.86	7.00	12.05	−32.392789	151.075506
3	8.35	12.90	7.05	12.06	−32.392795	151.075512
4	8.12	6.55	7.88	12.41	−32.393228	151.076596
5	8.47	10.01	7.73	12.44	−32.393541	151.077322
6*	–	–	–	12.45	−32.393602	151.077480
7	8.53	10.1	7.72	12.46	−32.393859	151.078011

* Sample dropped due to human error.

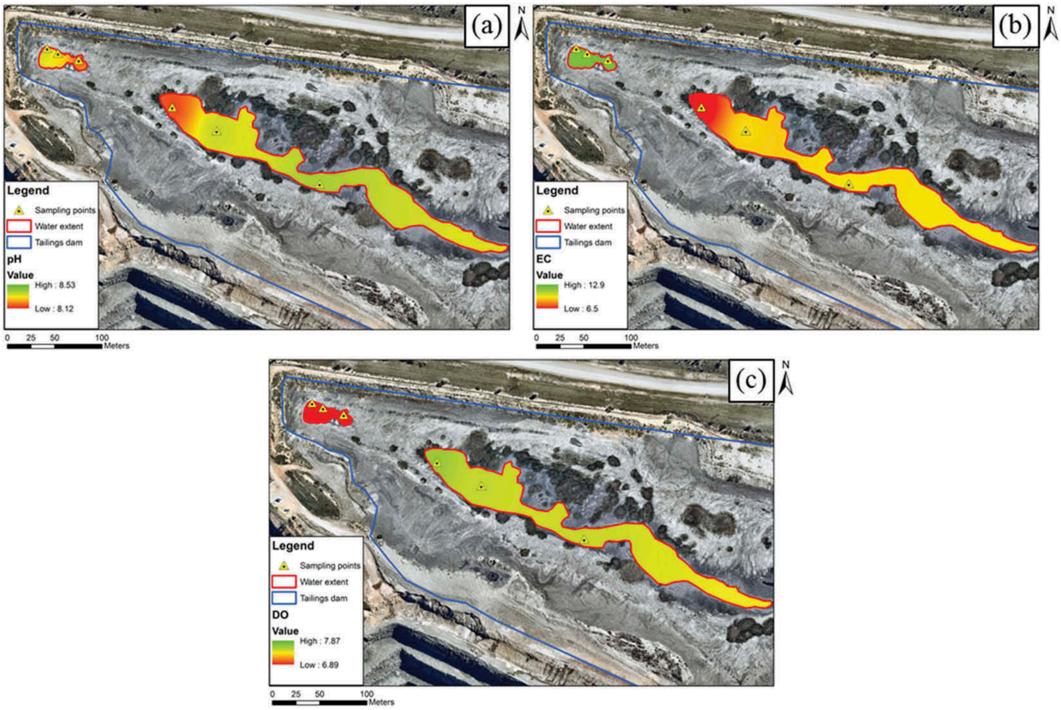

Figure 7. Interpolated water quality maps for (a) pH, (b) electrical conductivity (EC) and (c) dissolved oxygen (DO).

The UAV-IEPS provides a platform for the future of water quality monitoring and management on a mine site, particularly of TSFs. Using UAVs to collect water quality data sets is useful for the management of mine water in tailings. The system could be used to generate other kinds of surface water quality data sets, using appropriate water quality testing devices. The technology can benefit the mining industry and could provide new data for areas that were previously inaccessible such as pit water, water in abandoned mine sites and acid mine drainage. Use of remotely operated technology can also improve safety standards by increasing the frequency of monitoring, minimising the physical interaction of hazardous substances, and eliminating the risks associated with sampling in a hazardous environment.

6. Conclusion

The development of the IEPS for UAV-based remote water quality monitoring presents several opportunities to improve the effectiveness and efficiency of monitoring mining operations. The developed IEPS has been tested in both the laboratory and the in-field environment of a TSF. The developed prototype functioned flawlessly during the in-field trial, successfully collecting six samples from two tailing ponds. Rapidly emerging technologies such as 3D printing offer new design opportunities for these types of UAV-based water sampling systems. Further research including additional field experiments and routine flights using this system is warranted to address future design challenges.

This study identifies the following benefits and relevance of the developed system for the mining industry:

- safety: increasing the safety standards of mine environmental monitoring by removing personnel from the hazardous environment;
- accessibility: allowing water samples to be collected from water sources that could not be previously accessed such as pit water, TSFs, water in abandoned mine sites and acid mine drainage;

- environmental monitoring: producing a spatial-temporal profile of the hazardous environment through frequent in situ measurements of water quality;
- management: enabling more responsible mine operations based on maps of water quality, at suitable frequencies or sampling intervals, that are not physically possible without this system.

The study analysed and produced surface water quality maps for pH, DO and EC on a mine tailing site for the first time. The spatial profiles of water quality are unique and are useful for monitoring and management of short- and long-term risks to the mining operation. Being able to collect water samples from water sources across a mine site means that probable sources of poorer quality water can be identified, as a step towards appropriate management and monitoring strategies. An improved understanding of the distribution and magnitude of poor water quality (salinity, turbidity, acidity, metals, organics and other contaminants of concern) can result in better environmental outcomes for wildlife, aquatic ecosystems and sensitive downstream fresh water, and also reduce potential harm to personnel on-site. The research undertaken in this study is a strong base for future research to use UAV-based remote water sampling systems to aid mine water monitoring and management.

Acknowledgement

The authors thank Mr Shaun Leary and his team at Glendell Coal Mine, New South Wales, Australia, for their support in carrying out the fieldwork.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This independent research was funded by the Australian Centre for Sustainable Mining Practices (ACSMP), School of Minerals and Energy Resources Engineering, UNSW, Australia, as a PhD scholarship for the first author.

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