Practical Paper

A low-cost, open-source autonomous surface vehicle as a multipurpose waste stabilization pond monitoring platform

A. Cuppens, G. Menesse, E. Caligaris, O. Marecos and G. Wyseure

ABSTRACT

Although waste stabilization ponds (WSPs) are widely used in developing countries, monitoring data on their operational performance are scarce. Traditional methods for monitoring in-pond conditions, i.e. conducting hand held measurements from a small boat or installing fixed sensor networks, are not straightforward to realize and create an unhealthy working environment for field workers. A promising technology for the safe and efficient collection of monitoring data is a compact autonomous surface vehicle (ASV), capable of autonomous navigation along a predefined trajectory based on geographic coordinates and measurements in different places and depths. In this practical paper, the development process, technical details and functional testing results of a low-cost ASV for WSP monitoring are presented. Commonly available construction materials and electronic components were used to ensure affordability and reparability. The access to online tutorials and peer-support was crucial for assembling the open-source autopilot and data logger. The ASV demonstrated satisfactory performance for both the autonomous navigation as well as the georeferenced data logging of measurements at a real-scale WSP in Paraguay. This study demonstrates how the adoption of open-source hardware and software offers the flexibility for the wastewater professionals to develop customized DIY solutions for specific monitoring applications and working environments.

Key words | autonomous surface vehicle, monitoring, open-source, waste stabilization ponds

A. Cuppens (corresponding author)
G. Menesse
E. Caligaris
Facultad de Ciencias de la Ingeniería,
Universidad Paraguayo Alemana,
Lope de Vega 1279, San Lorenzo,
Paraguay
E-mail: *arnoud.cuppens@upa.edu.py*

O. Marecos
Empresa de Servicios Sanitarios del Paraguay,
José Berges 516, Asunción,
Paraguay

G. Wyseure
Department of Earth and Environmental Sciences,
KU Leuven,
Celestijnenlaan 200e, BE-3001 Heverlee,
Belgium

INTRODUCTION

Waste stabilization ponds (WSPs) are widely used in developing countries due to their very high efficiency in pathogen removal and low cost of construction, operation and maintenance (Kivaisi 2001). Phenomena such as underloading/overloading, hydraulic short-circuiting, thermal stratification and excessive sludge accumulation have a major impact on the treatment performance. Due to the generalized lack of monitoring data, in particular for remotely located WSPs, the wastewater managers are not aware about their actual operational performance (Cuppens *et al.* 2013).

A fundamental component of any WSP performance evaluation is the characterization of incoming wastewater and effluent (Pearson *et al.* 1987), which in general are easily accessible for inline sensor installation or sample collection. In contrast, the monitoring of conditions within the pond is less straightforward to realize. Conducting hand held measurements from a small boat (Fyfe *et al.*

doi: 10.2166/washdev.2018.110

2007) creates an unsafe and unhealthy working environment. Maneuvering of the boat across the pond must be done carefully in order to take measurements sufficiently close to the desired locations and minimize water column perturbation. A network of floating devices at fixed locations with sensors set at regular vertical intervals is an alternative in-pond monitoring approach (Abis & Mara 2006). This method still requires the use of a manned boat during installation. The overall equipment cost increases drastically with the number of measurement points. Therefore, any technological innovation allowing the safe and efficient collection of monitoring data within the WSP is welcomed.

One promising technology is a compact autonomous surface vehicle (ASV), capable of navigating autonomously along a predefined trajectory based on geographic coordinates, and, meanwhile, performing measurements at different locations within the pond. Initially, the ASVs deployed for water monitoring purposes were large, costly and complex, hence not an appropriate technology for monitoring WSP in developing countries, where financial resources are scarce and the working environment is challenging (Cuppens *et al.* 2013). Moreover, any breakdown/failure requires reparation or servicing by the supplier, which is both expensive and time consuming.

Fortunately, thanks to the contributions made by the open-source movement, the electronic devices and software required for developing such a low-cost ASV are nowadays accessible to the wider public. The Pixhawk (3DR 2017), one of the most famous open-source autopilots (AP) and heavily supported by the DIYdrones community (Kakaes *et al.* 2015), is available for approximately US$200. For obtaining a flexible and low-cost data logger that automatically georeferences the measurement data, one can use an Arduino UNO with a data logging attachment (such as the Adafruit Ultimate GPS Logger Shield) for an approximately combined cost of US$75 (Lockridge *et al.* 2016). Such equipment is easy to replace or repair with a minimum level of electronic knowledge.

In this practical paper, the development process, technical details and testing results of a low-cost, open-source ASV for WSP monitoring are presented. The applicability of the ASV technology is discussed and recommendations for future improvements are given. The overall goal is to demonstrate how the adoption of open-source hardware and software by wastewater professionals opens up a variety of opportunities for monitoring the operational performance of sanitary infrastructure in developing countries.

MATERIALS AND METHODS

Development approach

The objective was to construct a robust ASV, capable of navigating autonomously along a predefined trajectory, and, meanwhile, perform measurements at different predefined locations within the pond. In order to anticipate the challenging working conditions in developing countries, the following design guidelines for the ASV were added:

- use of low-cost and commonly available construction materials guaranteeing access to replacement parts in case ASV components get damaged during fieldwork;
- use of low-cost electronics and software for the autonomous navigation capability, by preference bought locally (thanks to the popularity of unmanned aerial vehicles, the required electronics can be ordered worldwide);
- flexible and low-cost set-up of measurement devices, consisting of a single open-source data logger that allows integration of a variety of environmental sensors;
- the ASV must fit comfortably within a standard car and must be easy to transport.

The development process consisted of two stages: first constructing a prototype based on existing recreational ASV projects (published on http://diydrones.com) to gain practical experience with the AP. Afterwards, the construction of a second, more robust ASV with an integrated winch, allowing the lowering/lifting of a sensor and data logging in an automated way.

Technical details of ASV

The design concept of a catamaran was selected for the ASV platform (see Figure 1) because multihull vessels demonstrate better navigation behavior and higher stability in comparison with monohulls (Luhulima *et al.* 2014).

The propulsion mechanism based on wind thrust was placed on top of the ASV in order to minimize the

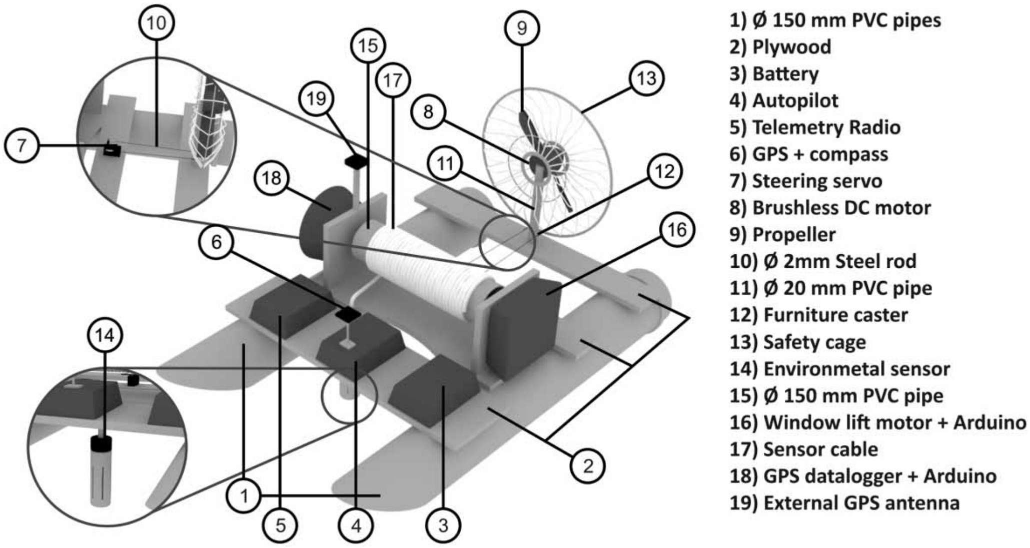


Figure 1 | Main components of the ASV.

disturbance of the water column below the ASV. The pontoons consist of two PVC pipes (1) connected by plywood (2). On top of the upfront plywood, plastic waterproof containers with the electronic devices – (3), (4), (5) and (6) – for autonomous navigation were attached. The main components of the propulsion system are a steering servo (7) and a brushless DC motor (8) with propeller (9). A pair of steel rods (10) links the servo to the motor mount, which is composed of a small diameter PVC pipe (11) standing vertically over a furniture caster (12). As such, the servo controls the rotation of the motor mount and attached DC motor with propeller. The safety cage (13) of a table ventilator was incorporated for protecting the operator against the propeller. As such, the ASV is a relatively standard application of autonomous navigation of a small catamaran.

More innovative is the mechanism for realizing measurements at different depths by means of a submerged environmental sensor (14). For this purpose a winch system was chosen, which consists of a horizontal rotating spool (15) supported by a wooden structure and driven by an electric window lift motor (16) protected in a plastic waterproof container. The spool is a PVC pipe spirally ribbed with a small, flexible plastic tube in order to facilitate the safe winding and unwinding of the sensor cable (17). The electronic devices for datalogging (18) are contained in a plastic waterproof container attached to and rotating together with the spool. A data logger was chosen with its own independent GPS for the registration of the location. An external GPS antenna (19) was attached to the data logger to improve accuracy. An overview of the electronic architecture of the ASV is presented in Figure 2.

The open-source Pixhawk (3DR 2017) was selected for achieving the autonomous displacement capability along a trajectory of predefined geographical coordinates called waypoints (WPs). This AP continuously receives information about the actual position of the ASV from a GPS sensor. Based on the comparison of the actual position and the next WP, adjustments are made to the steering in order to navigate the ASV towards the next WP. Sensors, such as compass, gyros and accelerometers, assist in achieving this objective. Via radio telemetry, the position of the ASV can be monitored in real time within the open-source ground control software Mission Planner (Oborne 2017) installed on a laptop. Adjustments to the planned trajectory can be made at all times via telemetry.

At the start of each monitoring mission, the user clicks the sequence of WPs on a map-layer available in Mission Planner (see Figure 3(a)) and sets a value for the WP radius defining how close the ASV has to come in order to be considered as having arrived. A time delay of 15 s is added to each WP, so that when the ASV reaches a WP,

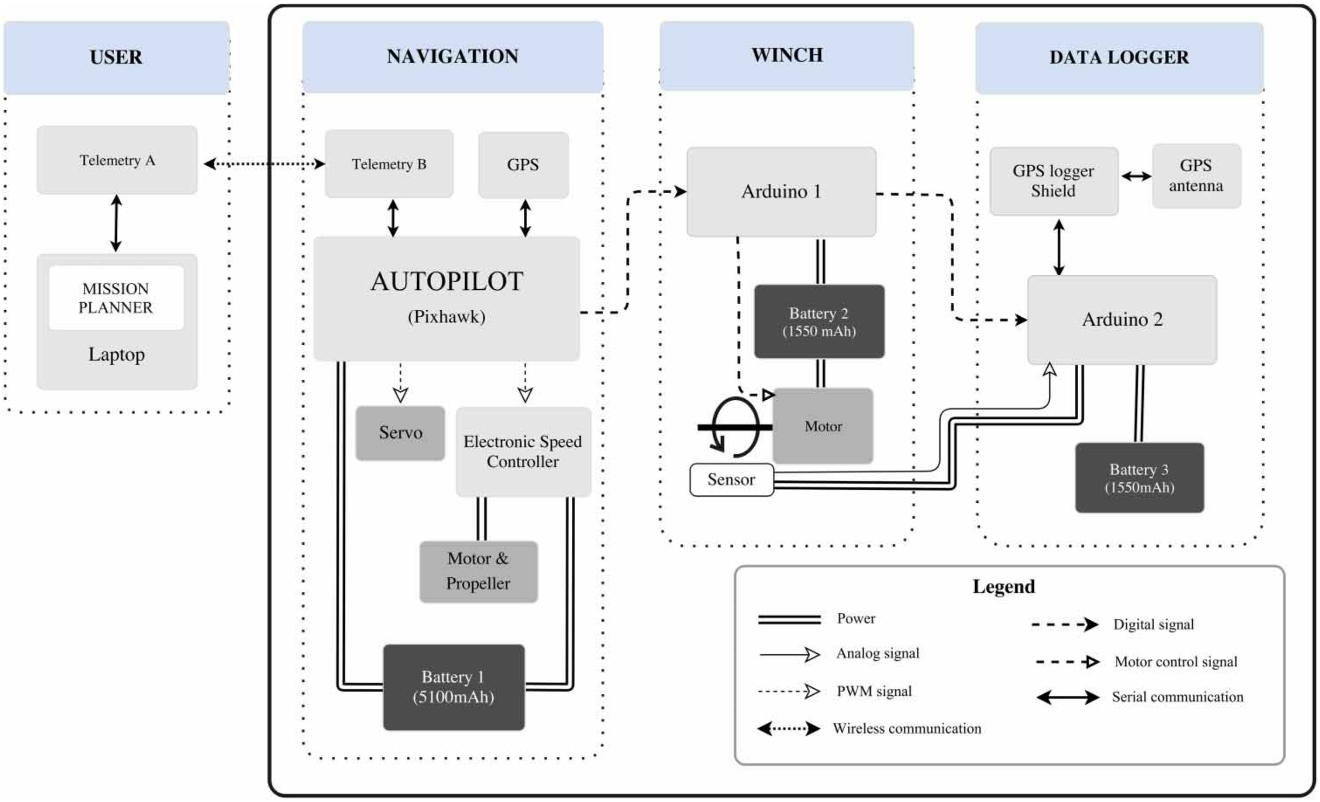


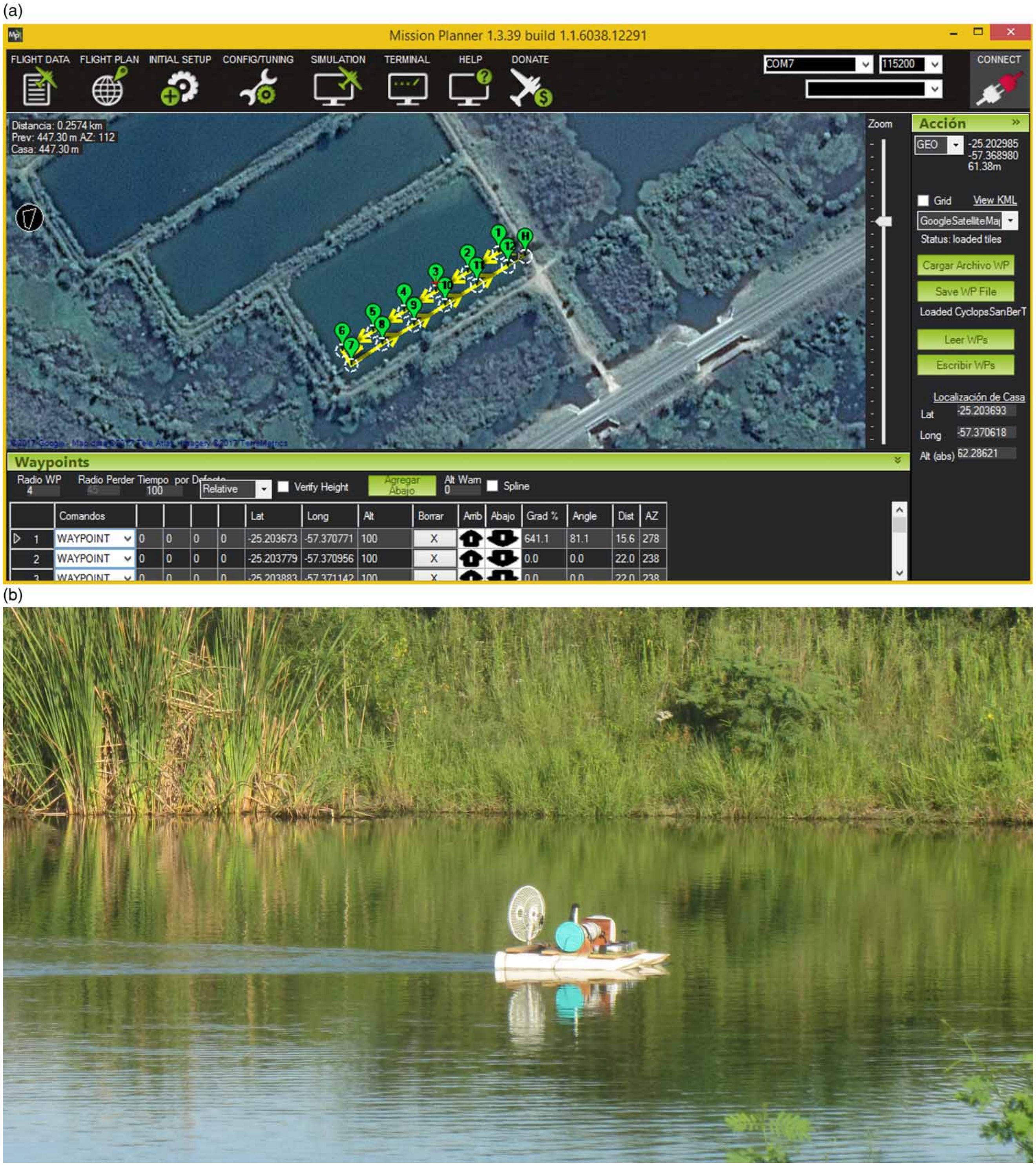
Figure 2 | Overview of the electronic architecture of the ASV.

the AP stops the motor automatically during the specified duration. The latter signal triggers the Arduino controlling the winch to execute the routine of a stepwise lowering of the sensor at preprogrammed depths, followed by the uplifting to the initial position. The data logger, consisting of an Arduino with attached Adafruit Ultimate GPS Logger Shield, is programmed to take a measurement at each sensor depth and will instantly save the measurement value on a mini SD card together with the geographical coordinates.

The total cost of the ASV platform (see Figure 3(b)) is approximately US$1350: US$1250 for electronics and US$100 for the construction materials for the platform and winch (PVC, wood, plastic containers, etc.). The most costly electronic components are the Pixhawk Kit (US$249), the radio remote control (US$200), the telemetry set (US$129) and the GPS uBlox (US$119). The unit price of one LIPO battery (5,100 mAh; 11.1 V) required for motor powering is US$40. The required amount of reserve batteries depends mainly on the total distance to be covered during a monitoring mission.

Functional testing

The navigation performance by the ASV was initially tested on a nearby lake with a recreational function. After satisfactory navigation tests, the ASV was tested on five events in the WSP of San Bernardino, located at a distance of 60 km from Asuncion, Paraguay. A grid of 36 measurement points was projected on a surface area of 0.9 ha. Taking into account the conservative estimate of the ASV travel distance per battery being 400 m, it was decided to divide the monitoring mission into three trajectories, each covering 12 WPs. The first three tests (29th December 2016; 10th January 2017; 13th January 2017) were carried out without lowering/lifting of the sensor (although pausing at WPs), while during the final two tests (3rd February 2017; 7th February 2017) measurements were taken at two different



Mission Planner 1.3.39 build 1.1.6038.12291

COM7 | 115200

Distancia: 0.2574 km
Prev: 447.30 m AZ: 112
Casa: 447.30 m

GEO -25.202985 -57.368980 61.38m

☐ Grid

GoogleSatelliteMap

Status: loaded tiles

Loaded CyclopsSanBerT

Localización de Casa
Lat -25.203693
Long -57.370618
Alt (abs) 62.28621

Radio WP 4
Radio Perder Tiempo 45
por Defecto 100
Relative
☐ Verify Height
Alt Warn 0
☐ Spline

	Comandos					Lat	Long	Alt	Borrar	Arrib	Abajo	Grad %	Angle	Dist	AZ
▷ 1	WAYPOINT	0	0	0	0	-25.203673	-57.370771	100	X	⬆	⬇	641.1	81.1	15.6	278
2	WAYPOINT	0	0	0	0	-25.203779	-57.370956	100	X	⬆	⬇	0.0	0.0	22.0	238
3	WAYPOINT	0	0	0	0	-25.203883	-57.371142	100	X	⬆	⬇	0.0	0.0	22.0	238

Figure 3 | (a) Mission Planner user interface and (b) photo of the ASV navigating on a WSP.

depths with a Cyclops sensor for logging the background concentration of Rhodamine WT.

The log files of the AP during the five missions allow the evaluation of the navigation performance (executed trajectories and behavior in the vicinity of WPs), while the log data registered by the GPS data logger during the final two missions provides useful information about the spatial accuracy of the measurements. The spatial accuracy is influenced by several factors such as the horizontal position accuracy of the GPS connected to the Pixhawk (2.5 m; Ublox), the GPS of the datalogger with attached external antenna (1.8 m; Adafruit), the selected WP radius (i.e. 2 m) and the drifting behaviour of the ASV platform during the timespan of measurement. In addition to a visual comparison, an approximate indicator for the spatial accuracy is determined, i.e. the average distance (m) between a programmed WP and the measurement as registered by the GPS data logger based on 36 WPs.

RESULTS AND DISCUSSION

Testing results

In Figure 4, the navigation results obtained during the five executed missions are presented for each of the three trajectories (trajectory one covers WPs 1–12, trajectory two WPs 13–24 and trajectory three WPs 25–36). One observes that the ASV was capable of reaching all 36 WPs during each of the five missions.

As expected, during the pausing at a WP, the ASV floats around but remains within an acceptable range (except once in WP 34). Regardless of what the heading is at the end of the pausing period, the ASV automatically recuperates an appropriate heading while continuing its course towards the following WP. A good example is the ASV behaviour in WP 30, where the trajectories demonstrate a U-turn before continuing to WP 31. Overall, one observes a very good repeatability of trajectories with minor differences.

In Figure 5, WPs are presented by squares and the registered measurements by dots. Based on visual inspection, one notices that the ASV has sufficient accuracy for collecting useful georeferenced monitoring data. The average distance between the WP and the registered measurement is 2.3 m with a standard deviation of 1.1 m. Although GPS accuracy could be increased (e.g. by RTK technology), this would not decrease the drifting during measurement and, therefore, has too limited an impact in order to justify the additional cost.

For a trajectory, the duration of navigation, including the pausing at the 12 WPs, was approximately 14 minutes. During light wind conditions, a single battery yields a

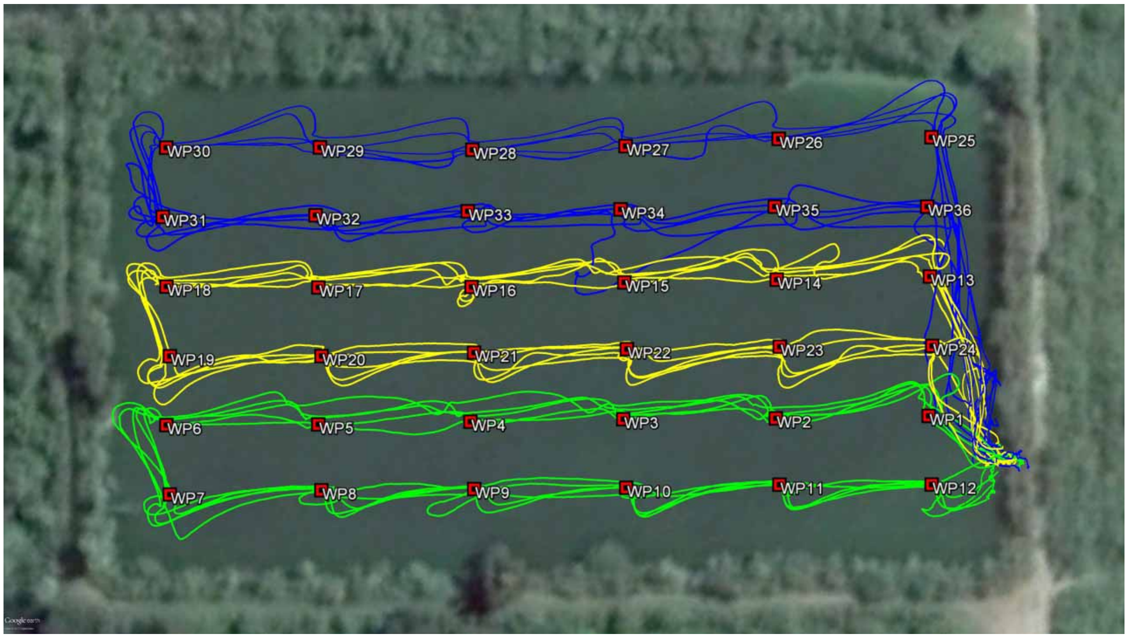


Figure 4 | ASV trajectories during five executed missions. Trajectory one covers WPs 1–12, trajectory two WPs 13–24 and trajectory three WPs 25–36. WPs are represented by squares.

Figure 5 | Locations of WPs (squares) as planned in Mission Planner and the measurement points as registered by the GPS data logger (dots).

travel distance of at least 400 m. Time for set-up and launch is typically 5–10 minutes, depending mainly on how quickly GPS lock is obtained and the duration of uploading the mission to the AP.

Technology applicability

The open nature of the ASV allows wastewater professionals to integrate almost any type of sensor according to their monitoring needs. As such, there exists a variety of potential applications for WSP performance evaluation. For instance, measuring water temperature, dissolved oxygen concentration and pH allows the assessment of the level of stratification (Fyfe *et al.* 2007). During tracer tests, the mapping of the tracer distribution within the pond (see Figure 6) is a valuable source of information for understanding internal flow patterns (Broughton & Shilton 2012). The ASV can also be equipped to measure the pond depth by means of a sonar to monitor sludge accumulation (Coggins *et al.* 2017).

The affordability and reparability of the ASV increases the likelihood of successful adoption in developing countries. Using standard components and readily available materials allows spare parts to be obtained easily and repairs can be executed locally. The fabrication of the platform and winch does not require any specialized equipment. The access to step-by-step tutorials and the peer-support by the open-source community allow users with minimum knowledge of electronics to assemble and customize the electronic kits for autonomous navigation and data logging. Important advantages of the ASV technology in comparison with traditional in-pond monitoring methods are minimal human exposure to wastewater, ease of transport and quick deployment. This makes the ASV particularly useful for wastewater managers aiming at the regular monitoring of WSPs located at multiple locations.

Limitations and future work

As the scope was the initial testing of a low-cost ASV for WSP monitoring, the current platform still needs to undergo a continuous improvement process before becoming a user-friendly and consolidated monitoring tool. The following improvements are recommended:

(1) Endurance: Currently, the battery-life of the ASV propulsion mechanism is limited. Although the time loss for changing batteries is acceptable, the main difficulty arises during continuous monitoring missions when batteries need to be recharged on-site. Charging a single

Figure 6 | Photo of the ASV during a Rhodamine WT tracer test in a WSP.

battery takes up to 1 hour and access to electricity is often not available. The following improvements are recommended:

- Solar powering: add lightweight, flexible solar panels to increase energy autonomy. As a reference, a 24-hour deployment has been achieved by a large, solar-powered ASV for monitoring oceans and inland lakes (Higinbotham *et al.* 2008; Dunbabin *et al.* 2009).
- Weight reduction: use lighter materials, in particular for the winch structure.

(2) Robustness and durability: Replacing the plastic food-storage containers by electrical enclosures increases robustness without a significant cost increase.

(3) Winch: Include features for a safer and more efficient winch, such as (1) automatically adjusting the maximum sensor depth based on in-situ depth readings and (2) motor auto-blocking preventing sensor uplift in case the cable gets stuck due to unexpected and unknown submerged obstacles.

(4) Real-time monitoring: Enable real-time follow-up of measurements through a permanent telemetry communication link between the data logger and laptop.

CONCLUSIONS

Since most WSPs are located in developing countries where field data are scarce (Sah *et al.* 2012), more efforts must be made to collect water quantity and quality data (Cuppens *et al.* 2013). In addition to the traditional monitoring of the incoming wastewater and effluent, measurements at multiple locations and depths within the WSP provide useful information. In this practical paper, the development and testing of a low-cost and open-source ASV for monitoring in-pond conditions was presented. The ASV demonstrated satisfactory performance for both the autonomous navigation as well as the georeferenced data logging of measurements. The WSP of San Bernardino, with a surface area of 0.9 ha, was covered by three trajectories with a total distance of approximately 1,100 m. Measurements were taken at two different depths for 36 programmed points. The total cost of the ASV is approximately US$1350, from which electronics takes up 90%. Its open nature allows the integration of almost any type of sensor according to user needs, making it a flexible, low-cost platform for performing a variety of in-pond measurements. Simplicity, affordability and reparability are key factors for adoption of this novel monitoring technology in developing countries.

ACKNOWLEDGEMENTS

This research was conducted within the framework of the PROCIENCIA program funded by CONACYT (Consejo Nacional de Ciencia y Tecnología – Paraguay). The authors would like to thank ESSAP (Empresa de Servicios Sanitarios del Paraguay) and the DIYdrones community.

REFERENCES

3DR 2017 *Autopilot Pixhawk (3DRobotics) Portal*. Available from: https://store.3dr.com/t/pixhawk (accessed 12 May 2017).

Abis, K. L. & Mara, D. 2006 Temperature measurement and stratification in facultative waste stabilisation ponds in the UK climate. *Environ. Monit. Assess.* **114**, 35–47.

Broughton, A. & Shilton, A. 2012 Tracer studies on an aerated lagoon. *Water Sci. Technol.* **65** (4), 611–617.

Coggins, L. X., Ghisalberti, M. & Ghadouani, A. 2017 Sludge accumulation and distribution impact the hydraulic performance in waste stabilisation ponds. *Water Res.* **110**, 354–365.

Cuppens, A., Smets, I. & Wyseure, G. 2013 Identifying sustainable rehabilitation strategies for urban wastewater systems: a retrospective and interdisciplinary approach. Case study of Coronel Oviedo, Paraguay. *J. Environ. Manage.* **114**, 423–432.

Dunbabin, M., Grinham, A. & Udy, J. 2009 An autonomous surface vehicle for water quality monitoring. In: *Proceedings of Australasian Conference on Robotics and Automation*, 2–4 December 2009. Australian Robotics and Automation Association (ARAA), Sydney, Australia.

Fyfe, J., Sivakumar, S. M., Hagare, S. C. & Jenkins, A. 2007 Dynamic variation of supernatant quality in a dairy shed waste stabilisation pond system. *Water Sci. Technol.* **55** (11), 245–255.

Higinbotham, J. R., Moisan, J. R., Schirtzinger, C., Linkswiler, M., Yungel, J. & Orton, P. 2008 Update on the development and testing of a new long duration solar powered autonomous surface vehicle. In: *Proceedings of IEEE/MTS OCEANS 2008*, 15–18 September 2008. IEEE, Quebec City, Canada, pp. 1–10.

Kakaes, K., Greenwood, F., Lippincott, M., Dosemagen, S., Meier, P. & Wich, S. 2015 *Drones and Aerial Observation: New Technologies for Property Rights, Human Rights, and Global Development. A Primer*. New America, Washington, USA. Available from: http://drones.newamerica.org/primer/ (accessed 12 May 2017).

Kivaisi, A. K. 2001 The potential for constructed wetlands for wastewater treatment and reuse in developing countries: a review. *Ecol. Eng.* **16** (4), 545–560.

Lockridge, G., Dzwonkowski, B., Nelson, R. & Powers, S. 2016 Development of a low-cost Arduino-based sonde for coastal applications. *Sensors* **16**, 528.

Luhulima, R. B., Setyawan, D. & Utama, I. 2014 Selecting monohull, catamaran and trimaran as Suitable passenger vessels based on stability and seakeeping criteria. In: *Proceedings of the 14th International Ship Stability Workshop*, 29 September–1 October 2014. Marine Technology Centre, UTM, Kuala Lumpur, Malaysia, pp. 262–266.

Oborne, M. 2017 *Mission Planner Software*. Available from: http://ardupilot.org/planner/ (accessed 12 May 2017).

Pearson, H. W., Mara, D. D. & Bartone, C. R. 1987 Guidelines for the minimum evaluation of the performance of full-scale waste stabilization pond systems. *Water Res.* **21** (9), 1067–1075.

Sah, L., Rousseau, D. P. L. & Hooijmans, C. M. 2012 Numerical modelling of waste stabilization ponds: where do we stand? *Water, Air, and Soil Pollution* **223** (6), 3155–3171.

First received 5 July 2017; accepted in revised form 13 October 2018. Available online 7 November 2018