Bandini, Filippo; Lüthi, Beat; Bauer-Gottwein, Peter

Unmanned aerial systems (UASS) for monitoring water surface elevation, bathymetry, surface velocity and discharge in streams

Hydrolink

UNMANNED AERIAL SYSTEMS (UASS) FOR MONITORING WATER SURFACE ELEVATION, BATHYMETRY, SURFACE VELOCITY AND DISCHARGE IN STREAMS

BY FILIPPO BANDINI, BEAT LÜTHI & PETER BAUER-GOTTWEIN

To date, hydrometric monitoring (i.e. monitoring of water surface elevation, bathymetry, flow velocity and discharge) of rivers and streams has relied primarily on either in-situ measuring stations or in-situ surveys. In-situ surveys are expensive, require the operator to access the area and cannot be conducted during extreme events, such as floods. State-of-the-art UAS-borne sensors can provide hydrometric observations of streams with high accuracy, high spatial resolution and at a lower cost than in-situ surveys.

"The single water drop never feels responsible for the flood"- Douglas Adams, English author. Floods (and water scarcity) have a large impact on individuals, communities, agriculture and industries; however, data availability from in-situ monitoring stations is declining worldwide for both political and economic reasons [1], [2]. Thus, most river networks are gauged at relatively few locations only with low spatial resolution and small streams (less than 100 m wide) may not be gauged at all. Optimization of river maintenance and flood prediction requires cutting-edge sensing technology. Satellite sensing technology is rapidly evolving to improve the observation and prediction of surface water and thus prevent natural disasters. Satellite altimeters have been successful in monitoring water surface elevation in large rivers, but are ineffective for smaller streams due to low spatial resolution. On the other hand, Denmark has established a large and expensive in-situ monitoring and maintenance program of its streams. Denmark has a dense network of rather small streams (ca. 48 000 km of streams are less than 2.5 m wide, 14 500 km are between 2.5 and 8 m,
1 500 km are more than 8 m wide), which are causing floods in agricultural areas resulting in significant property damage and crop yield losses. Conveyance and shape control of the small Danish streams costs approximately 20-30 million euros per year. Vandløbsregulativer (watercourse regulations) prescribe that each municipality is obliged to maintain the river shape or conveyance set by the current regulation. For this reason, 15 000 to 20 000 km of public rivers in Denmark are surveyed with in-situ measurements of bathymetry and discharge every 3-10 years. The majority of these streams are regulated by shape (bathymetry) control, with less than 5%

Figure 1. UAS in action to monitor a Danish stream

regulated by conveyance control (rating curves). These expensive surveys are conducted by human operators and are essential for targeting river maintenance, i.e. river vegetation cutting and riverbed clean-up. Maintenance operations are expensive and detrimental to the river ecological status, but are necessary to avoid floods.

Thus, recurring questions among researchers and practitioners working with Danish streams are "How can we improve the monitoring system for optimizing river maintenance and flood prediction? Can we deploy a technology to retrieve hydraulic observations of inland surface water bodies, whenever and wherever it is required, with (i) high accuracy, (ii) high spatial resolution and (iii) at a reasonable cost?". Unmanned Aerial Systems (UASs), a new kit in surveyors' toolbox, have changed our way to "access" and monitor the environment. Indeed, UAS can monitor remote areas delivering real time data. Compared to satellite monitoring, they ensure high spatial resolution, repeatability of the flight missions and good tracking of the water bodies. Compared to manned aircrafts, UASs are low-cost and easy-to-manoeuvre platforms that can retrieve observations with higher temporal resolution, potentially including periods of hydrological interest, such as floods and droughts. Figure 1 shows a picture of a UAS flying above a Danish stream to retrieve hydrometric observations. Nevertheless, UASs face several constraints: vibrations, limited size, weight, and electric power available for the sensors and inability to fly in extreme weather conditions.

Several previous studies have used photogrammetry to estimate Water Surface Elevation (WSE), i.e. height of water surface above mean sea level [3]–[6]. However, there are a number of serious limitations: water transparency causes through-water images and the ever-changing features on the water surface, such as ripples or turbulence, complicate identification of homologous points in the bundle adjustment. For this reason, WSE is generally estimated by identifying points on the shoreline, i.e. points at the interface between land and water, which are supposed to be at the same elevation as the nearby water surface away from the shoreline. However, this technique requires the operator to survey Ground Control Points (GCPs) and necessitates high computational time to process images. Furthermore, when the shoreline method is applied, the operator has to identify the shoreline points either manually or through automatic edge detection algorithms, which is highly complicated in densely vegetated rivers. In earlier publications [7]–[9] we presented the first studies on UAS radar altimetry. Studies were conducted to measure water surface elevation in Danish rivers and lakes, and in the famous and unique cenotes and lagoons of the Yucatan peninsula, Mexico. An accuracy of few centimetres and a spatial resolution of few decimetres were achieved. This accuracy and spatial resolution are higher than any other spaceborne radar or airborne LIDAR altimeter. Furthermore, compared to photogrammetry, this technique does not rely on any GCP, and requires a significantly smaller amount of survey time and post-processing computational time (approximately 1/1000 of processing time). Unlike photogrammetry, UAS radar altimetry can also measure WSE in rivers surrounded and overhung by aquatic vegetation and trees. In Figure 2, we show a WSE profile retrieved with our UAS radar altimetry technique of the stretch of a Danish stream.

Surface flow velocity can be estimated with nonintrusive image analysis techniques applied to frames retrieved from the UAS-borne RGB

Filippo Bandini is a Postdoctoral researcher at DTU Environment, Technical University of Denmark. His research is currently focused on UAS-borne remote sensing of hydraulic measurements and assimilation of these innovative observations into hydrodynamic models. He is primarily developing, investigating and integrating lightweight and accurate sensors to retrieve water level, speed, and bathymetry measurements from UAS.

Beat Lüthi studied Mechanical Engineering at ETH Zürich and graduated at ETH in 2002 in the field of fluid turbulence. Until 2012, Beat Lüthi was leading the hyromechanics group at IfU ETH, specialized in the fields of image based particle tracking velocimetry and turbulence small scale dynamics. In 2012 Beat Lüthi founded the ETH spin off company photrack Ltd. Photrack has developed the now patented technology SSIV to measure surface flow velocities and discharge rates with cameras. For the resulting products DischargeKeeper and the Discharge App there is growing business in Europe, USA, Africa, Central Asia and China.

Peter Bauer-Gottwein is professor in hydrology and water resources management at DTU Environment. Research focus areas are hydrological modelling, hydrogeophysics, earth observation for inland water applications and hydroeconomic modelling. Scientific highlights include ground-breaking work on the integration of time-lapse gravity observations with hydrological models; Exploration and modelling of the world's largest karstic groundwater aquifer on the Yucatán Peninsula, México; Assimilation of satellite radar altimetry observations to hydrologic forecasting systems; Integration of water and power system models for joint resource management. He has significant international experience, including Southern Africa, Mexico, China, Central Asia. He has authored 70+ scientific articles in international journals indexed in ISI Web of Sciences and 4 book chapters.

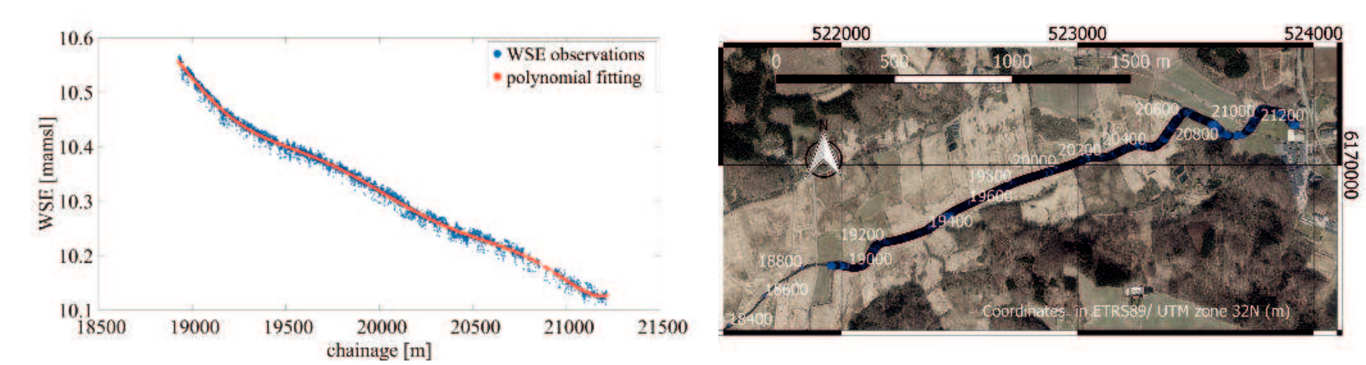
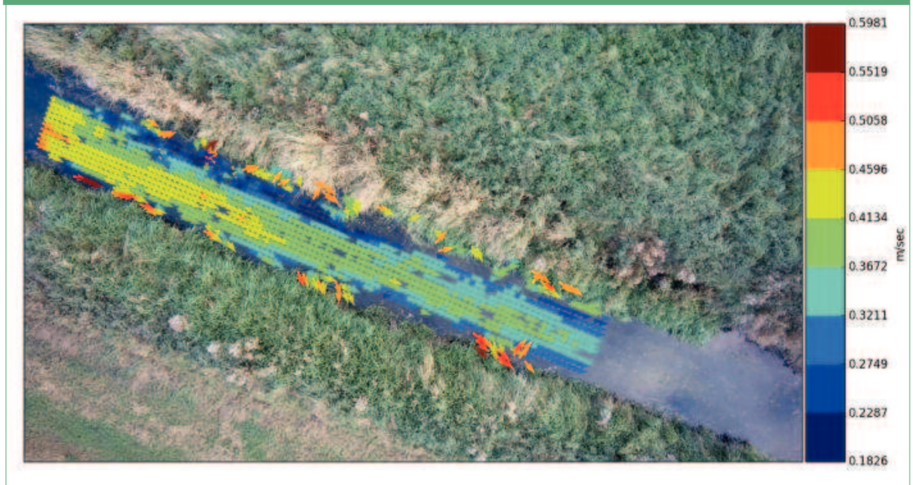


Figure 2. WSE profile measured for a stretch of Vejle Å (Jutland, Denmark). Left panel shows UAS-borne WSE observations (blue dots) and the profile fitting of these observations (red line). Right panel shows the 2-km stretch where WSE observations (blue dots) were retrieved, with white labels showing the progressive river chainage

camera. These image techniques commonly require that tracer particles are on the water surface and that they travel with the same velocity as the surface flow. Surface flow velocities are reconstructed by determining the displacements of the tracer particles (such as leaves, foam, artificial particles) between two subsequent frames. These image analysis techniques are generally differentiated between two categories, based on the Eulerian or Lagrangian specification of the flow field: Particle Image Velocimetry (PIV) [10]–[12] or Particle Tracking Velocimetry (PTV) [13] [14], respectively. Surface Structure Image Velocimetry (SSIV) [15], [16] is a special variant of the PIV cross-correlation technique and is aimed at reducing the negative influence on the observations caused by i) glare and shadows on the water surface, and ii) lack of traceable features [17]. Figures 3 and 4 show the SSIV estimation of the surface velocity field and the extracted surface velocity profile in a Danish stream. In this case, no artificial particles were added on the water surface and the algorithm was able to reconstruct the water flow by identifying natural particles such as foam or ripples generated by water turbulence.

Surface velocity observations are essential to highlight flow patterns. Furthermore, surface velocity can also be used to estimate discharge following standard procedures such as the ISO standard EN ISO 748:2007. To do so it is necessary to have also the water depth profile, which can be measured either with an in-situ bathymetric survey, or with UAS-borne bathymetric observations obtained from state-of-the-art bathymetric LIDARs [18] or UAS-tethered sonar [19]. To convert from surface velocity to discharge, we have to adopt assumptions about the vertical velocity profile in the water column. Thus, UAS can supply hydrometric data, such as WSE, bathymetry and discharge, needed to inform hydrodynamic modelling and river management. High spatial-resolution WSE profiles along streams emerge as a new dataset that can help us understand how rivers are affected by vegetation growth and optimize river maintenance, such as vegetation cutting and riverbed clean-up. In our vision, hydrometric UAS-observations are essential not only for small scale management of flood protection/modelling and river restoration, but also to establish a river monitoring UAS-network at regional/national scale. However, this requires that Beyond the Visual Line Of Sight (BVLOS) fully autonomous flights are allowed by the regulators. BVLOS flights will significantly increase UAS potential for hydrometric monitoring, including river maintenance optimization and flood prediction. ■

Figure 3. Water surface velocity field observations in Værebro å (Denmark)



References

[1] F. Tauro, J. Selker, N. Van De Giesen, T. Abrate, R. Uijlenhoet, M. Porfiri, S. Manfreda, K. Caylor, T. Moramarco, J. Benveniste, G. Ciraolo, L. Estes, A. Domeneghetti, M. T. Perks, C. Corbari, E. Rabiei, G. Ravazzani, H. Bogena, A. Harfouche, L. Broccai, A. Maltese, A. Wickert, A. Tarpanelli, S. Good, J. M. Lopez Alcala, A. Petroselli, C. Cudennec, T. Blume, R. Hut, and S. Grimaldia, "Measurements and observations in the XXI century (MOXXI): Innovation and multi-disciplinarity to sense the hydrological cycle," *Hydrol. Sci. J.*, vol. 63, no. 2, pp. 169–196, 2018.

[2] R. Lawford, A. Strauch, D. Toll, B. Fekete, and D. Cripe, "Earth observations for global water security," *Curr. Opin. Environ. Sustain.*, vol. 5, no. 6, pp. 633–643, 2013.

[3] P. Leduc, P. Ashmore, and D. Sjogren, "Technical note: Stage and water width measurement of a mountain stream using a simple time-lapse camera," *Hydrol. Earth Syst. Sci.*, vol. 22, no. 1, pp. 1–11, 2018.

[4] E. Ridolfi and P. Manciola, "Water level measurements from drones: A Pilot case study at a dam site," *Water (Switzerland)*, 2018.

[5] A. S. Woodget, P. E. Carbonneau, F. Visser, and I. P. Maddock, "Quantifying submerged fluvial topography using hyperspatial resolution UAS imagery and structure from motion photogrammetry," *Earth Surf. Process. Landforms*, vol. 40, no. 1, pp. 47–64, 2015.

[6] H. Pai and S. Tyler, "Re-examining data-intensive surface water models with high-resolution topography derived from unmanned aerial system photogrammetry," *Am. Geophys. Union, Fall Meet. 2017, Abstr. #H41D-1463*, 2017.

[7] F. Bandini, J. Jakobsen, D. Olesen, J. A. Reyna-Gutierrez, and P. Bauer-Gottwein, "Measuring water level in rivers and lakes from lightweight Unmanned Aerial Vehicles," *J. Hydrol.*, vol. 548, pp. 237–250, 2017.

[8] F. Bandini, M. Butts, T. V. Jacobsen, and P. Bauer-Gottwein, "Water level observations from unmanned aerial vehicles for improving estimates of surface water-groundwater interaction," *Hydrol. Process.*, 2017.

[9] F. Bandini, A. Lopez-Tamayo, G. Merediz-Alonso, D. Olesen, J. Jakobsen, S. Wang, M. Garcia, and P. Bauer-Gottwein, "Unmanned aerial vehicle observations of water surface elevation and bathymetry in the cenotes and lagoons of the Yucatan Peninsula, Mexico," *Hydrogeol. J.*, pp. 1–16, Apr. 2018.

[10] F. Tauro, M. Porfiri, and S. Grimaldi, "Surface flow measurements from drones," *J. Hydrol.*, vol. 540, pp. 240–245, 2016.

[11] F. Tauro, M. Porfiri, and S. Grimaldi, "Orienting the camera and firing lasers to enhance large scale particle image velocimetry for streamflow monitoring," *Water Resour. Res.*, vol. 50, no. 9, pp. 7470–7483, 2014.

[12] M. Jodeau, A. Hauet, A. Paquier, J. Le Coz, and G. Dramais, "Application and evaluation of LS-PIV technique for the monitoring of river surface velocities in high flow conditions," *Flow Meas. Instrum.*, vol. 19, no. 2, pp. 117–127, 2008.

[13] F. Tauro, R. Piscopia, and S. Grimaldi, "PTV-Stream: A simplified particle tracking velocimetry framework for stream surface flow monitoring," *Catena*, 2019.

[14] F. Tauro, R. Piscopia, and S. Grimaldi, "Streamflow Observations From Cameras: Large-Scale Particle Image Velocimetry or Particle Tracking Velocimetry?," *Water Resour. Res.*, 2017.

[15] B. Lüthi, T. Philippe, and S. Peña-Haro, "Mobile device app for small open-channel flow measurement," in *7th Intl. Congress on Env. Modelling and Software*, 2014, vol. 1, pp. 283–287.

[16] B. Lüthi, Thomas Philippe, and S. Peña-Haro, "Method and system for determining the velocity of a moving fluid surface," EP Nr: 3 018 483, 2018.

[17] J. P. Leitão, S. Peña-Haro, B. Lüthi, A. Scheidegger, and M. Moy de Vitry, "Urban overland runoff velocity measurement with consumer-grade surveillance cameras and surface structure image velocimetry," *J. Hydrol.*, 2018.

[18] G. Mandlburger, M. Pfennigbauer, M. Wieser, U. Riegl, and N. Pfeifer, "Evaluation Of A Novel Uav-Borne Topo-Bathymetric Laser Profiler," *ISPRS - Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.*, vol. XLI-B1, pp. 933–939, Jun. 2016.

[19] F. Bandini, D. Olesen, J. Jakobsen, C. M. M. Kittel, S. Wang, M. Garcia, and P. Bauer-Gottwein, "Technical note: Bathymetry observations of inland water bodies using a tethered single-beam sonar controlled by an unmanned aerial vehicle," *Hydrol. Earth Syst. Sci.*, vol. 22, no. 8, pp. 4165–4181, Aug. 2018.

Figure 4. UAV-borne surface velocity profile compared to in-situ surface velocity probe measurements, Værebro å (Denmark)