Experiences from the use of Unmanned Aerial Vehicles (UAV) for River Bathymetry Modelling in Norway

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Sammendrag

Erfaringer med bruk av ubemannede fly (UAV) for bunntopografimodellering i Norge.
Kunnskap om undervannsmorfologi er essensielt, hvis man vil bruke hydrodynamiske modeller for å undersøke habitatforhold eller konsekvenser av vannkraftreguleringer i elver. Tradisjonelle manuelle eller båtbaserte bunntopografioppmålinger er tidskrevende og noen ganger farlig eller umulig på grunn av store strømhastigheter. Fjernmålingsmetoder basert på flyfoto fra lav høyde kan være et alternativ.

Denne artikkelen beskriver en pilotstudie hvor vi testet et ubemannet fly (UAV) for bunntopografimodellering basert på flyfoto i Surna. Optisk bunntopografimodellering bygger på sammenheng mellom vanndybder og luminansverdier i et flyfoto. Lyzengas (1981) dypvannskorreksjonsmetode ble brukt i kombinasjon med en kalibrering for lavvann. Modellen krever oppmåling av noen vanndybder i felt for kalibrering. Metoden ble brukt for to cirka en kilometer lange elvestrekninger. Flyfotoene ble tatt med en Microdrone som fløy 70 til 135 m over bakken. Studien viste at optiske bunntopografimålingsmetoder basert på UAV har et stort potensial, hvis datainnsamlingen blir godt forberedt og finner sted under passende værforhold.

Summary

Knowledge of underwater morphology provides essential input to hydrodynamic model applications as part of studies of habitats and the effects of hydropower regulation in rivers. Traditional manual or vessel-based bathymetry surveys are time-consuming and sometimes dangerous or impossible to implement in rivers with strong currents. Remote sensing techniques based on low altitude airborne colour photography may represent an alternative.

This paper describes a pilot study carried out in the river Surna, a gravel-bed river in Mid-Norway, to test the use of Unmanned Aerial Vehicles (UAV) for river bathymetry modelling based on optical remote sensing. Optical bathymetric modelling relies on the relationship between water depth and radiance values captured in an aerial image. Lyzenga's (1981) deep water correction method was used in conjunction with shallow-water calibration. Modelling requires some field-measured depth values for calibration. The method was applied by acquiring aerial photographs along two approximately 1-kilometre river reaches, using a Microdrone flying at heights ranging between 70 and 135 metres.

The pilot study showed that the application of UAV-based optical remote sensing methods has great potential for bathymetric surveys in fluvial settings, provided that the survey is carefully prepared and performed under favourable weather conditions.

Introduction

The field of river restoration and management has developed enormously in recent decades, and the use of 2D or 3D hydrodynamic models to investigate habitat conditions and the effects of hydropower regulation in natural rivers is on the increase. Applications require a high-resolution digital terrain model (DTM) for the entire river reach, incorporating both underwater and terrestrial areas, figure 1.

Underwater topography is known as bathymetry. Early bathymetry measurement techniques used hand lead-lines lowered from a vessel's side. They were replaced successively by vessel-mounted single-beam, and later multi-beam, echo sounders. Some direct survey methods for terrestrial areas such as total stations and hand-held Global Positioning Systems (GPS) can also be used in very shallow water, provided that currents are not too strong and the river bed accessible. However, all direct, manual or vessel-based bathymetry approaches are time-consuming and sometimes dangerous or impossible to implement in rivers with strong currents.

For this reason remote sensing techniques have become increasingly popular, and "fluvial remote sensing" (FRS) has emerged as a subdiscipline within the remote sensing and river sciences (Marcus and Fonstad 2008, Carbonneau and Piegay 2012). Traditional remote sensing approaches include satellite imagery, aerial photography and laser scanning. FRS bathymetry data can be obtained by bathymetric laser scanning (blue/green LiDAR) or optical methods based on aerial photography. However, blue/green LiDAR has limited accuracy in fluvial settings, and remains unsuitable for mapping in shallow waters (Hohenthal et al. 2011, Legleiter 2012). In contrast, optical bathymetry models have been shown to produce good results in rivers (Legleiter and Roberts 2009, Flener et al. 2010).

Two broad types of platforms can be used for the acquisition of aerial images. The first involves conventional aircraft and unmanned aerial vehicles (UAV). UAVs are easy to pilot and can fly at very low altitudes, enabling them to deliver very high resolution imagery at relatively low cost. Before use however, researchers must be fully aware of domestic airspace regulations. Small, lightweight

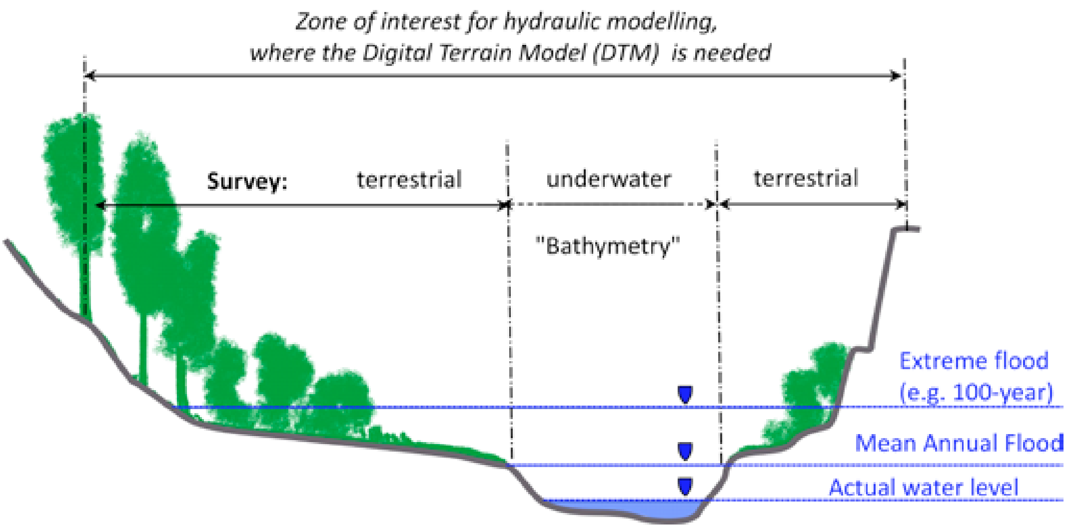

Figure 1. Diagram showing the terrestrial and underwater zones which must be surveyed prior to hydraulic modelling studies.

UAVs operating at low altitudes (less than 400 ft or 120 m) in rural areas and within the pilot's line of sight usually present no problems. However, the Norwegian Civil Aviation Authority (CAA) currently has no regulations governing UAV operations. Applications for use are considered individually based on an assessment of a thorough description of planned activities and a risk analysis, including corrective measures in the event of failures. Insurance against injury or damage to third parties must be taken out, and safety levels must be deemed acceptable (Raustein 2011).

In this study, we describe results from a pilot study using low-altitude airborne colour photography for bathymetry modelling along the Surna, a gravel-bed river in Norway. The work was funded via the EnviPeak project as part of a programme headed by the Centre for Environmental Design of Renewable Energy (CEDREN). We take this opportunity to thank all our project partners for their co-operation; SINTEF Energy Research, the Norwegian University for Science and Technology (NTNU) in Trondheim, the University of Turku (UTU), the Finnish Geodetic Institute (FGI) and AeroVision AS.

Methods and study sites

The optical remote sensing method

Optical bathymetry modelling is based on the relation between water depth and radiance values. In simple terms it works on the principle that deep water appears darker in aerial photographs than shallow water. Lyzenga (1981) developed the following deep-water correction algorithm to linearize the relationship between pixel values or digital numbers (DN) in each band and depth:

$$X_i = \ln(L_i - L_{si}) \qquad (1)$$

where X_i is a variable linearly related to water depth in band i, L_i is the observed brightness and L_{si} is the deep water radiance within the same band.

The algorithm exploits the fact that light attenuation in water is exponential, according to the Beer-Lambert law of logarithmic decay. Besides depth, the reflected signal contains input from other factors such as substrate type, water colour and sediment load. Lyzenga's deep-water correction algorithm attempts to isolate the depth signal from the image by discarding the influence on digital radiance data of sediments and other constituents in the water column. The algorithm was developed for coastal bathymetric modelling and uses deep water radiance to isolate depth data. In other words, it is necessary to know in advance the radiance at a location where the water is deep enough for the river bed not to have any influence on measured radiance values. In order to establish the regression between the deep-water corrected radiance values and depth, the method requires calibration in the form of directly measured depth values.

In rivers, it is often impossible to find an area deep enough from which to retrieve the L_{si} parameter (Legleiter et al. 2009). Previous studies have thus either employed in-situ spectroscopy (Gilvear et al. 2007), or have obtained L_{si} values from additional images taken in deep water zones from outside the study area (Flener et al. 2011). Flener (2013) presented a new method for calibrating the deep water radiance in shallow water conditions without the need to use in-situ spectrometry. In the present study, Lyzenga's (1981) algorithm, combined with Flener's (2013) shallow water calibration method, was tested in the Surna river, together with two other methods described in Dierssen et al. (2003) and Stumpf et al. (2003).

The following conditions have to be met in order to ensure successful application of the method (Flener et al. 2010):

The water must be clear.

The water surface must be transparent and not too rough, i.e., no "white-water" rapids.

There must be an unobstructed view of the river reaches under analysis, i.e., no overhanging trees, shadows or ice cover.

Results will also be affected by substrate variability. The Lyzenga algorithm assumes uniform substrate properties, although variations in substrate can be distinguished during data analysis (e.g. Winterbottom & Gilvear, 1997; Flener et al. 2010).

Figure 2. An aerial image of the study sites at Harang and Svean along the river Surna. (Source: www.norgeibilder.no).

Study sites, project partners and work stages

The UAV-based optical imagery method was tested along two approximately 1-kilometre river reaches in the river Surna in Rindal and Surnadal municipalities in Mid-Norway, figure 2. The flow regime in the Surna has been altered since 1968 due to the operation of a hydropower station. The study site at Harang is situated downstream of the Trollheim power plant outlet, which has a maximum operating flow of 38.5 m^3/s. The mean annual discharge along the river at Harang Bridge is 48 m^3/s (Halleraker et al. 2007). The study site at Svean is located approximately 8 kilometres below Harang, downstream of the confluence of the Vindøla tributary.

For this project, optical remote sensing to determine shallow water bathymetry for use in models was carried out at the University of Turku (UTU) in Finland. Initially it was planned that the Finnish researchers would use their own equipment (UAV and sensors) to acquire aerial images along the Surna. However, this required the preparation of documents needed as part of an application to the CAA in Norway to acquire a permit to fly a UAV. This process was regarded as disproportionate in relation to the scale of the pilot study. It was thus decided to distribute the tasks of UAV photography and image processing among the different partners. SINTEF Energy Research commissioned AeroVision AS, a Norwegian company in possession of all necessary

Work stage	Content	Project partners
Fieldwork	❍ Establishment of ground control targets ❍ Camera calibration ❍ UAV photography ❍ Direct measurement of depth reference points	SINTEF NTNU Trondheim University of Turku (UTU) Aero Vision AS
Image processing	❍ Image evaluation and adjustment (such that illumination is consistent for all images) ❍ Geo-referencing of image mosaics based on measured ground control targets	A. Krooks (UTU/FGI)
Bathymetry modelling	❍ Processing of calibration data ❍ Preparation of image data (exclusion of shady areas etc.) ❍ Bathymetric modelling (e.g. Lyzenga's method) including data training and validation	C. Flener (UTU) SINTEF
Model evaluation	Investigation of model plausibility and accuracy	UTU, SINTEF, NTNU

Table 1. Summary of work stages and allocation of tasks among the project partners.

CAA permits, to carry out the UAV flights and supply aerial photography to the project. UTU's role was to process the photographs to produce a bathymetric model of the relevant river reaches. Table 1 provides a summary of the work stages involved and the allocation of tasks among the project partners.

Fieldwork

The aerial images and calibration data were acquired on 2 and 3 August 2011. There was close collaboration in the field and all involved partners played an active part.

The selected UAV platform was a Microdrone MD4-1000, figure 3a, weighing 5kg, including camera equipment (Canon EOS 550 D + 18-55 IS lens). The camera arrangement was calibrated on the ground using photogrammetric calibration targets, and all moving elements were taped in place to prevent unwanted movement during flight. The images were obtained using a remote trigger operated manually at intervals of about one second. The flight height ranged from 70 to 135 metres. Variable light conditions during the survey made conditions less than optimal. For this reason, four flights were carried out at Harang, and three at Svean, in order to provide a series of images from which the best could be selected. A storm event on the evening of 2 August 2011 resulted in high water turbidity, causing the final flight at Svean to be delayed until about noon on 3 August, when the river water became clearer.

In order to provide geo-referencing of the aerial images it was necessary to establish ground control targets points (GCP) at regular intervals on both sides of the floodplain, figure 3b. The exact locations of the GCP points, and the calibration water levels and bed elevations in shallow water zones, were determined using differential GPS combined with a Real Time Kinematic (RTK) satellite navigation technique. At the Svean site, not all GCP locations could be determined in the field due to technical difficulties.

A remote controlled vessel with an on board Acoustic Doppler Current Profiler (ADCP; Sontek RiverSurveyor M9) was used to acquire depth data in the deeper river zones. The sonar component of the ADCP measures depths >0.18 metres with an accuracy of 2.5%.

Image processing and bathymetry modelling

The images obtained from all flights were quality-assessed by UTU and FGI. In the cases of Harang and Svean, flight numbers 4 and 3 respectively were judged to have yielded the best images. For the most part, quality issues were linked to reflections of the sky on the water surface and variations in illumination during the period when the flights were carried out.

Figure 3. a) Microdrone MD4-1000 (Owner: AeroVision AS); b) Preparation of the ground control targets and GPS equipment.

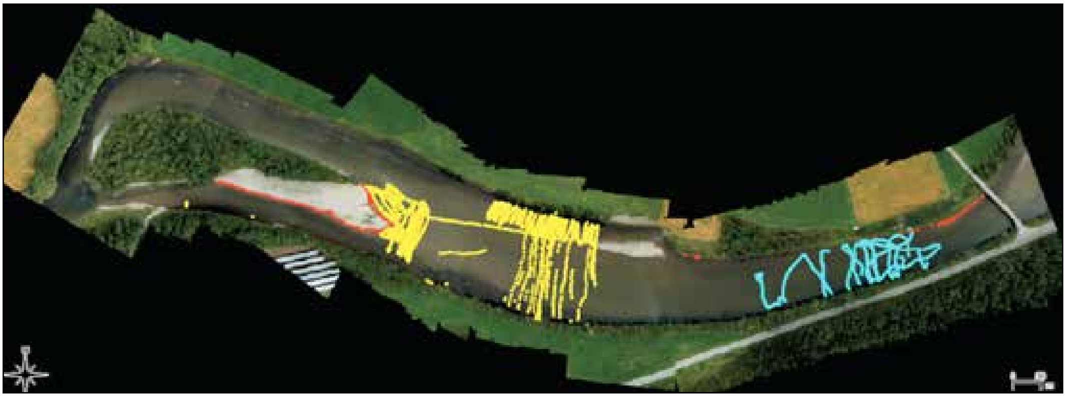

Figure 4. Overlay of the image mosaic and directly measured points for the Harang site. Yellow: bed level points, Red: Shore line points, Cyan: ADCP depth points.

All images revealed a certain lack of sharpness, probably due to the properties of the camera lens. Variable focal length zoom lenses are always less than optimal for aerial surveys compared to fixed focal length lenses, and kit lenses such as the one used in this study are made of plastic and often suffer from minor imprecision in the alignment of the lens elements. This manifests itself in the form of slight image blurring, particularly at the larger aperture settings required to offset vibrations of the airframe.

The image mosaics were geo-referenced using the GPS-measured GCPs. The final image mosaics were produced with 10 cm ground resolution. File conversion and image processing (including corner shade reduction and lens correction) were supported by the software packages Adobe Photoshop CS4, iWitness and Socet Set 5.5. The geographical information systems (GIS) Quantum GIS and ArcGIS10 were used to carry out various geo-processing tasks. The river bed points measured by the RTK-GPS in water depths shallower than those which the ADCP could measure were converted to depth by computing an interpolated river surface based on water level values measured from the shore.

Red and Green image bands were used to construct the bathymetric models. The Lyzenga (1981) model and ratio-based models developed by Dierssen et al. (2003) and Stumpf et al. (2003) were also tried out. Measured depths determined by the ADCP and the converted river bed data (Figure 4) were used to calibrate and assess the models. Deep-water radiance was computed using 100-fold random sub-sampling with an 80% training set. In order to avoid possible bias related to the sampling of calibration points, the model equation was also derived using 100-fold random sub-sampling using an 80% training set. Models were calibrated separately for the 10 cm and 15 cm raster images, based on the respective radiance values extracted from these images. The raster images were also resampled into a 50 cm raster.

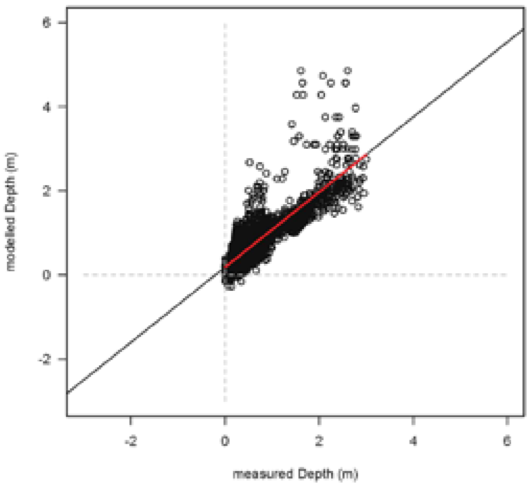

Figure 5. Modelled depth vs. measured points for the Harang site (50 cm raster model).

Results and discussion

Results and quality of the image mosaics

Based on the tested bathymetric models, the Lyzenga model in combination with the shallow-water calibration method presented in Flener (2013) yielded the best results. Figure 5 shows the results for Harang, where there was good agreement between measured and modelled water depths, with just a few outliers.

The bathymetry model derived from the aerial images is presented in figure 6. It provides a nearly complete depth map in the form of a raster data set with a spatial resolution of 0.5 metres. This resolution was chosen as being compatible with the prevailing coarse riverbed substrate grain sizes.

Closer inspection of the bathymetry model shows that some areas close to the river banks are absent, in particular along the deepest section on the left bank. Here the river bed was obscured by overhanging trees, and no depth information could be derived from the aerial image. Some “no data” pixels are identified in the more central parts of the river. These are related to the presence of dark-coloured algae and moss patches, figure 7, in locations where the calibra-

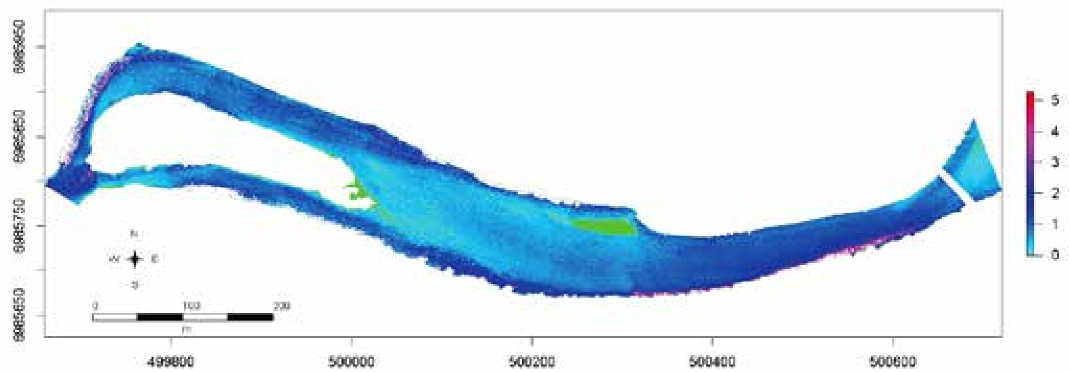

Figure 6. Bathymetric model of the Harang site. Water depths are given in metres.

Figure 7. Dark patches of aquatic vegetation (Svean site).

ted colour-depth relationship was outside the application window. These patches are observed in shallow water areas at both the Harang and the Svean sites.

The results of the bathymetry modelling at the Svean site were less satisfying for several reasons. Firstly, the quality of the aerial images was inconsistent and also poorer than at Harang due to variable light conditions during the period when the flights were carried out, and issues linked to camera lens quality. The image mosaic was more blurred and displayed artefacts caused by strong cloud reflections on the water surface, in particular in areas where the majority of calibration measurement points were located, figure 8. Secondly, the number of ground control targets available was lower at Svean, which resulted in larger geo-referencing errors.

Conclusions and recommendations

A UAV-based optical remote sensing technique based on the Lyzenga (1981) algorithm combined with Flener's shallow-water calibration method (Flener 2012) was tested at two sites on the Surna River, a gravel-bed river in Mid-Norway.

At the Harang site, the method provided a bathymetry map with adequate levels of accuracy and precision. At the Svean site, results were less accurate due to unfavourable light conditions in conjunction with suboptimal camera equipment and other technical problems. The latter issues were to a large degree related to the fact that this survey was a pilot study in which the flight team, field technicians, and those responsible for image processing were working together for the first time in the field. Experience obtained from the Surna River survey will enable future bathymetry flights to be organised more effectively. Below we present a summary of recommendations for future applications of UAV-based bathymetry modelling in Norway:

- The use of one's own UAV field equipment requires a resource-demanding process to obtain permission from the Norwegian Civil Aviation Authority. It may thus be preferable to join forces with private sector operators who have the necessary permits in place.
- A high quality photographic survey requires specific meteorological conditions.

Figure 8. Artefacts in the mosaic image for Svean caused by strong cloud reflections.

The weather should be dry, preferably slightly overcast, with stable light conditions throughout the period during which flights are carried out. If such conditions cannot be guaranteed, time should be scheduled for waiting on weather and possible repeat flights. It may not be possible during post-processing to correct for uneven illumination or reflections on the water surface.

- Only images taken when water is clear can be used for bathymetry modelling. This excludes aerial photography surveys during floods or after heavy storm events. The presence of dark-coloured vegetation in rivers will also raise complications.
- Fieldwork must be carefully prepared in order to avoid equipment failures. Sufficient ground control targets must be recorded throughout the survey area on both river banks (approx. 1 control along each bank spaced at 100 metre intervals).
- Depth measurements used for calibration may be acquired at a variety of locations, but must cover the entire range of water depths and substrates encountered in the study area.

Even the most advanced processing methods cannot rectify errors arising from poor image quality resulting from the presence of reflections, shadows or vegetation, limited camera resolution or inadequate field data quality. In the present study, the use of an inexpensive variable focal length kit lens restricted the sharpness of the aerial photographs at wider aperture settings. In order to ensure high-quality images, we recommend instead the use of high-quality fixed focal length wide-angle lenses. These deliver sharp images and facilitate broad coverage at lower flight heights, this providing better resolution at ground level.

Our study has shown that the application of UAV-based optical remote sensing methods has great potential as an aid to improving the effectiveness of bathymetric surveys used in fluvial studies. The technique provides a means of obtaining a contiguous bathymetric surface at the reach scale, without the interpolation of sparse ground data. UAV-based riverine mapping will probably play an increasing role in future.

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