WATER SURFACE AND VELOCITY MEASUREMENT- RIVER AND FLUME

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ABSTRACT:

Understanding the flow of water in natural watercourses has become increasingly important as climate change increases the incidence of extreme rainfall events which cause flooding. Vegetation in rivers and streams reduce water conveyance and natural vegetation plays a critical role in flood events which needs to be understood more fully. A funded project at Loughborough University is therefore examining the influence of vegetation upon water flow, requiring measurement of both the 3-D water surface and flow velocities. Experimental work therefore requires the measurement of water surface morphology and velocity (i.e. speed and direction) in a controlled laboratory environment using a flume but also needs to be adaptable to work in a real river.

Measuring the 3D topographic characteristics and velocity field of a flowing water surface is difficult and the purpose of this paper is to describe recent experimental work to achieve this. After reviewing past work in this area, the use of close range digital photogrammetry for capturing both the 3D water surface and surface velocity is described. The selected approach uses either two or three synchronised digital SLR cameras in combination with PhotoModeler for data processing, a commercial close range photogrammetric package. One critical aspect is the selection and distribution of appropriate floating marker points, which are critical if automated and appropriate measurement methods are to be used. Two distinct targeting approaches are available: either large and distinct specific floating markers or some fine material capable of providing appropriate texture. Initial work described in this paper uses specific marker points, which also provide the potential measuring surface velocity. The paper demonstrates that a high degree of measurement and marking automation is possible in a flume environment, where lighting influences can be highly controlled. When applied to a real river it is apparent that only lower degrees of automation are practicable. The study has demonstrated that although some automation is possible for point measurement, point matching needs to be manually guided in a natural environment where lighting cannot be controlled.

1. INTRODUCTION

The modelling of water flow in natural watercourses by computational fluid dynamics (CFD) incorporates several uncertainties due to the great complexity of the phenomena involved at assorted scales. An overlooked factor reducing water conveyance and therefore increasing flooding incidence is natural waterborne vegetation, which varies both temporally and spatially. A funded project at Loughborough University is therefore examining the influence of such riparian vegetation upon water flow, requiring detailed measurement of both the 3D water surface and surface flow field velocities. A laboratory flume provides the ideal environment to capture detailed empirical data in a controlled environment. However, there is a concern that real processes and interactions can be overlooked unless limited experimental work is conducted on a real river to avoid issues relating to scale.

This paper reports on the use of close range digital photogrammetry, to measure both the topographic surface created by a dynamic and flowing water and surface velocity vectors representing the surface flow field. A key aspect was to develop a technique that could be used in both a laboratory flume environment but could also be applied on a real river. Access to just inexpensive hardware and software is required, through the use of a pair of synchronised digital SLR cameras and proprietary close range photogrammetric software.

2. WATER SURFACE AND VELOCITY MEASUREMENT- PAST WORK

Water elevation or “stage” is routinely measured at many river locations but is always restricted to recording elevation at a single point through time, normally for providing flood warnings. Measuring the true water surface therefore requires sampling elevations at multiple locations in space, at an appropriate density and, ideally captured at an instant in time. The scientific literature reveals only a few instances where this has been achieved.

Thomson *et al*. (1999) generated elevation maps representing the water surface of a reach of the North Saint Vrain Creek, Colorado at a range of discharges. Their data appear to have been collected by level and staff using a series of cross-sectional surveys, typically adopted at the time. The availability of total stations and terrain modelling software subsequently helped to improve the ease of data collection, by removing the need to measure along a linear line. However, such approaches still required the manual movement of the prism and consequently a surface which strictly was not captured at an instant in time.

The ability of the camera to freeze motion has long been recognised. Fraser and McGee (1995) used synchronised large format CRC-1 cameras to capture 71 floating targets during the filling of a lock in the USA. Quoted accuracy was 2 cm, achieved at a frequency of 8 Hz during the eight minutes required for a 26m to lift cycle. Chandler *et al*. (1996) also used two synchronized analogue cameras in an oblique perspective. Two Hasselblad ELX cameras, modified to include a reseau plate, were used to measure the confluence of a pro-glacial meltwater channel, immediately downstream of the Upper Arolla glacier in Switzerland. They used 60 polystyrene fishing floats as marker points, constrained by six fishing lines. Images were scanned and off–the-shelf image processing software was used to measure the centroids of each target. A self-calibrating bundle adjustment was then used to derive XYZ coordinates and consequent digital elevation models (DEMs).

Stereo image sequences have been used to capture the dynamics of waves in a range of studies. Piepmeir and Waters (2004) review the use of stereopairs methods for measuring water waves created in laboratory flumes. In particular, they describe the problem of creating texture on the surface, which is sufficiently distinct and unique to facilitate measurement. They note how various authors have "polluted" the water, utilizing specialized lighting to provide suitable texture that can be measured. This is a key problem for measuring a material that is generally reflective and transparent. Their own solution involved generating a fine mist to provide an appropriate texture and minimize reflections, but do not provide the details necessary to achieve this.

Both Santel *et al*. (2004) and de Vries *et al*. (2010) apply stereo methods to capture breaking surf waves in the more challenging outdoor coastal environment. Both studies used comparatively simple point matching methods to generate digital surface models. Santel (2004) achieved this in an area of 200×200 m^2, represented by 20,000 conjugate points generated from 200 manually measured seed locations. Accuracies were difficult to estimate because of the lack of control but comparisons with a tide gauge suggested differences of 5 cm were typical. de Vries *et al*. (2010) applied stereo photogrammetry also, but in both the flume and field environment; taking advantage of a pier to support the two synchronised cameras. They fully describe the use of a standard normalised correlation method to achieve image correspondences. Accuracies were also assessed by comparing elevations with the tidal gauging station, but by averaging elevation across time and space. A more useful comparison was possible in the flume study, through the use of a pressure sensor mounted on the flume bed. Water depth comparisons through time revealed good correspondences and an overall RMSE error of 34mm. The authors stressed the importance of illumination and visual texture also. In particular, the benefits of an overcast sky creating naturally diffuse illumination of the sea surface. Examining the images acquired by Santel *et al*. (2004), it can be also seen that overcast conditions were prevalent.

Of perhaps increased relevance, Han and Endreny (2014) describe recent work in which they were able to use automated DEM extraction using a synchronised pair of digital images to measure the water surface. This was achieved using fine wax powder particles (0.3-0.8 mm diameter), which appears to create an appropriate texture under normal lighting conditions. The technique has been applied to a flume environment and they report excellent accuracies of 0.3 mm using cameras mounted just 1.3 m above the water surface. However, distributing non-biodegradable wax particles does not appear appropriate when working in the field environment.

3. THE MEASURING SYSTEM

Examination of the literature and indeed past work conducted by the first author suggested that a viable system based on digital photogrammetry could be developed. A key issue controlling the photogrammetry design is the type of targeting or more correctly "seeding particles" to be used. The overall adopted methodology is described in the subsequent section.

3.1 Targeting/seeding particles

Two distinct targeting approaches appear to be viable, each having their own strengths and weaknesses. If large and visually distinct targets are adopted (e.g. Fraser and McGee, 1995; Chandler *et al*., 1996) then it is possible to determine both surface morphology and velocity, if a sequence of images is required. However, the number and distribution of points is critical if a dense surface representation is to be created. Automation in the measurement chain can be challenging, particularly if the frequency of an image sequence is incompatible with the predicted flow velocity. Alternatively, if a measurable surface texture can be distributed evenly that generates image patches which are consistent from different camera positions and not affected by random spectral reflections, then there is the potential of creating a dense morphological representation fully automatically, using either stereo (e.g. Han and Endreny, 2014) or even perhaps MVS DEM generation methods. Surface water velocities could also be potentially possible using a PIV-based approach, although discrete targets could not be tracked individually.

The work conducted so far has used the former targeting solution, involving the sourcing of appropriate floating marker points. Selection of such markers has always been challenging and there are a range of requirements, which are often mutually exclusive. To allow full automation in the measurement process targets need to appear sufficiently distinct and spherical in an image sequence. If working in a river, then ideally they need to be biodegradable or at least collectable to avoid polluting the natural environment. This is not such an issue when working on a laboratory flume, but any material must be retrievable and must not damage expensive infrastructure such as filters or pumps. After trying a range of materials, including biodegradable packing chips (Chandler *et al*, 2008), translucent plastic spheres originally manufactured for roller ball-based deodorants were selected. These are mass manufactured and therefore reasonably cost-effective. They are also available in a range of sizes and approximately 200 spheres of both 20 mm and 10 mm diameter were purchased from Weener Plastics, UK Ltd for less than £100. The spheres also had an unexpected but very desirable quality when imaged using a standard SLR with Flash. The translucent and spherical shape appears to generate a small bright spot from the reflected flashlight (Figure 1). This is located at the centre of the sphere and at a fixed distance above the actual water surface and critically is independent of viewing direction. This allows the image point measured on multiple synchronised frames to represent a true point in 3-D space.

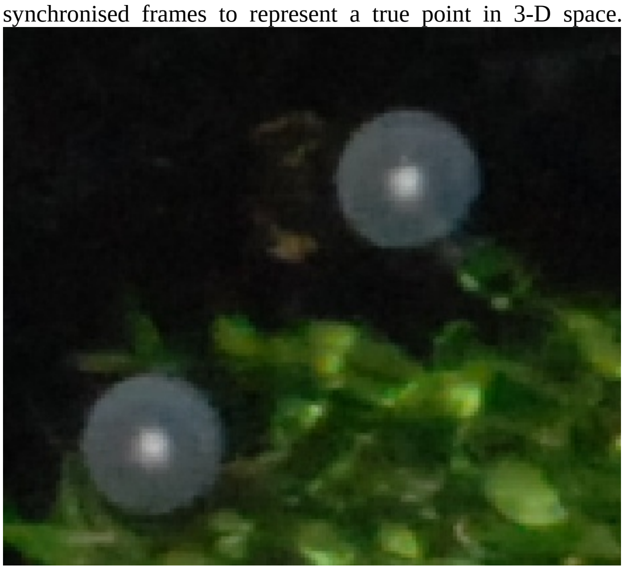

Figure 1 Sharp target complete with bright central spot

3.2 Imaging

Two Nikon D80 digital cameras were available for basic image acquisition, with a third Nikon D7000 potentially available. These are moderately priced digital SLR type cameras (10 and 15 MP) and were equipped with either a 24 or 28 mm fixed focus lens. Cameras can be mounted either vertically or obliquely on standard camera tripods. These provide the flexibility to achieve a convergent configuration for either flume or field application, with a desired base to distance ratio of approximately 1:7. The flowing water clearly creates a dynamic measurement problem, so obtaining synchronisation between the two exposures is critical. This has been achieved by constructing an electronically controlled triggering mechanism that creates a coincident electronic pulse along two standard Nikon MC-DC1 cables. Tests revealed that coincident exposures can be achieved to up to 1/1000th of a second, although all automated features (focus/exposure etc.) must be disabled. In addition, all other camera settings must be identical otherwise synchronisation accuracies drop to 1/300th of a second.

Two exposure and imaging strategies have been adopted so far. Primary data acquisition has involved using the inbuilt flash in “standard mode”, which achieves a distinct sharp image of the sphere frozen in space (Figure 1 and Figure 4). Typical exposure settings for the darker and more demanding laboratory application include: shutter priority, f-16, 1/60th second, ISO: 1000. The alternative has created a deliberate blur by using “SLOW flash synchronisation”. Typical exposure settings include: aperture priority, f-11, 1/10th second, ISO: 1600. This creates a sharp image of the sphere at the initial instant of exposure, but then a noticeable and measurable trail which is a function of the exposure time and sphere velocity (Figure 2). It was found necessary to vary the ISO setting to achieve a trail of an appropriate length, which can then allow determination of surface water speed and direction of flow at a point.

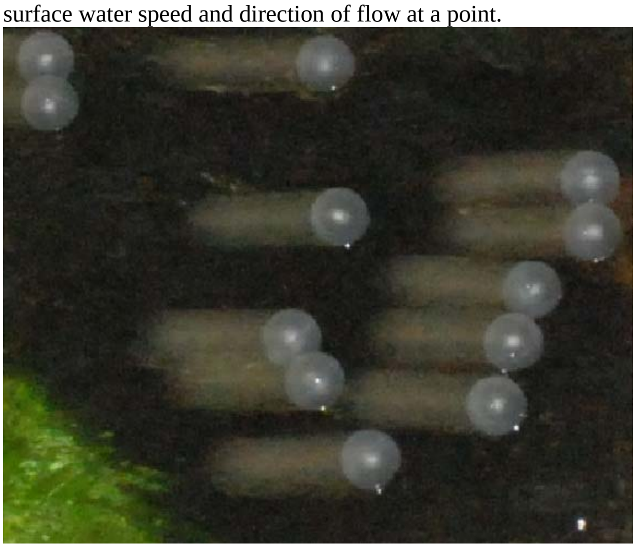

Figure 2 Deliberateley blurred targets for velocity determination

3.3 Control

Although control is not essential for the photogrammetry, obtaining appropriate scaled and oriented data is critical for relating measurements to gravity induced flows. Control could be achieved using PhotoModeler “Ringed Automatically Detected” or RAD targets of appropriate size, each easily coordinated using a standard reflectorless Total Station (Figure 3). For the river application, targets were located on both sides of the channel mounted temporarily on stakes hammered into the bank.

For the flume work, two control bars each with 10 RAD targets were placed upon the flume sides and again coordinated using the total station (Figure 4). The control survey then provides a real world coordinate system, where the z-axis is oriented to local gravity at a known scale.

Figure 3 Control survey and general layout for field application

Figure 4 Control layout for laboratory application with evenly distributed “sharp” targets

3.4 Seeding distribution/collection

One of the challenges that had to be overcome was to distribute the floating marker points evenly across the water surface during photo acquisition. Initial attempts that involved simply throwing the spheres manually proved unsatisfactory. Distribution was uneven and once wet, spheres tended to stick together or conglomerate. The difficulty was eased by constructing four narrow wooden “strip containers” which could be preloaded with spheres just prior to the test. These straddled the flume and could be tipped to provide a consistently spaced row of spheres. By repeating this sequentially using all preloaded strip containers, an even distribution down the channel could be achieved with practice (Figure 4).

The plastic spheres are non-biodegradable and it is therefore unethical to allow them to escape into the natural environment. Spheres could be easily collected in both the flume and field by using two wooden and hinged spars which straddled the river.

The spars guided the spheres into two fishing nets and proved both portable and effective (Figure 5).

Figure 5 Two hinged wooden spas used for collecting spheres

3.5 Water surface data-processing

The PhotoModeler scanner software was available and chosen for all photogrammetric data processing and attempts were made to automate as many of the required data processing stages as possible. The two cameras were calibrated using the PhotoModeler camera calibration option, simply by acquiring convergent imagery of a RAD-based control field at the required fixed focusing distance. This is a fully automated process and recovers all of the elements of inner orientation necessary to model the internal camera geometry.

The processing necessary for water surface determination, required the following key stages:

1. identifying appropriate synchronised pair, key criteria including: accurate synchronisation, even distribution of seed points across the flume/river and targets located within areas of interest (i.e. in the vicinity of vegetative elements);
2. An "Automated Smart Points" project was used to load in the required image pair and establish an initial orientation.
3. Automatically measure "RAD" targets and process to confirm that these have been measured and detected correctly.
4. Introduce the desired datum using "External Geometry Explorer" by loading and an appropriate "Coded Target Definition File" containing the control coordinates.
5. Automatically marks positions of the seed points using "Automatic Target Marking". Critical parameters included: diameter range in pixels and circularity or "Fit Error". (Typical parameters: White Dots, Fit Error: 0.4, Diameter: 5-20 pixels).
6. Three water surface points were then manually "Referenced" across the pair to obtain three 3-D coordinates to define an approximate plane representing the water surface. For convenience, these points were placed on a new layer named: "wsurf".
7. The remaining surface points were then "Automatically Referenced", guided using the approximate plane defined by the three "wsurf" points.
8. The project was then "Processed" and consequent 3-D model and residuals examined (Figure 6) to ensure no gross errors had been introduced.
9. Data was then "exported" and a fixed vertical offset was subtracted to account for the difference between the bright measured spot and the actual water surface (4mm for the 20 mm diameter spheres).

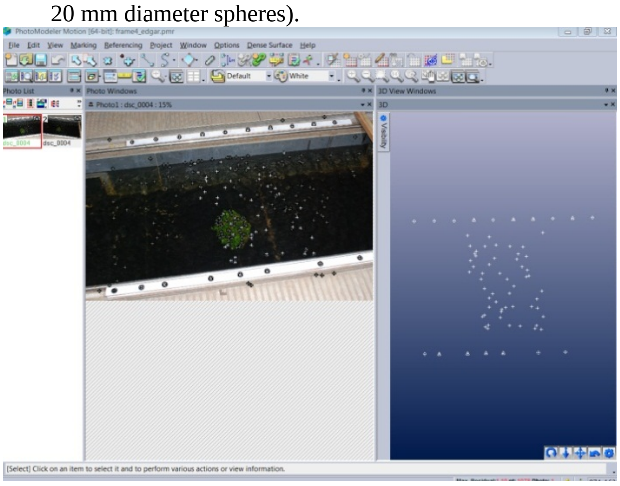

Figure 6. Automated measurement using PhotoModeler

Although some manual interaction was required, it was found that user assisted automatic processing methods could typically generate 30 to 40 water surface points in approximately 10 to 20 minutes. However, it was found that lighting played a critical control (Section 4.1). If automated methods were not viable or became too time consuming, then manual marking and referencing provided a workable alternative.

3.6 Surface velocity data-processing

The measurement necessary for detecting surface velocity was broadly similar, but required greater manual intervention. Initial stages necessary to detect and determine the three-dimensional positions of the bright spots was identical. These represented the positions of the spheres at the instant of the flash (Figure 2). The end of the trail then had to be estimated and measured manually. The length of this 3-D vector divided by the exposure time (recorded in the jpeg EXIF header) then provides the velocity of the sphere. The assumption then has to be made that the sphere is moving at the same velocity of the water, which appears appropriate.

It was decided to convey the length and orientation of these velocity vectors by simply generating an orthophoto in the XY plane from the oblique imagery (Figure 7).

4. DISCUSSION

Although the previous section describes the targeting solution and key processing stages adopted, there are a range of critical controls which need to be discussed. In addition, an understanding of how the derived morphological and superficial velocity data will be used in modelling of the flow, before planned future work is identified.

4.1 Critical controls

One of the main reasons why measuring a water surface presents challenges is the naturally reflective properties of water. The water surface acts as a dynamic and multifaceted mirror, which creates an infinite number of reflections which vary continually, both spatially and temporally.

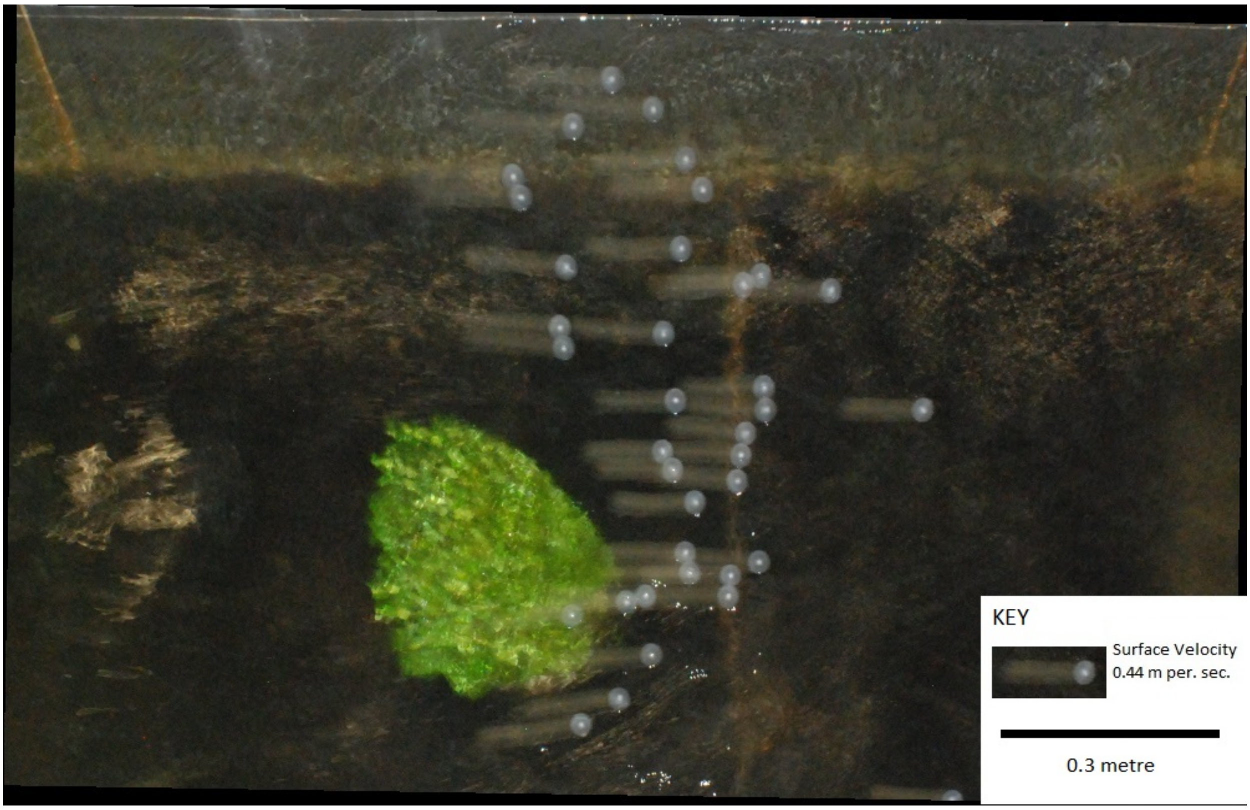

Figure 7 Scaled orthophoto showing velocity vectors in the XY plane, flume application

It also has to be recognised that a different pattern of reflected points is captured by each image in a synchronised pair. If manual measurement approaches are adopted then the human brain can interpret and identify the required target floating marker points. However, if automation is sought, then spurious bright spots created by the reflected light and areas of reduced contrast due to "flair", need to be avoided. In the flume environment this was achieved by setting up a plastic canopy (e.g. a garden gazebo proved effective!) was positioned and placed over the top of the test area so that it prevented the multiple ceiling lights being reflected into the lens. This approach was not practicable in the outdoor field environment, where the scale of application was much larger. Although initial fieldwork tests proved successful, two other approaches are recommended and will be tested. Measurements could be restricted to days where the conditions are both overcast but bright. The alternative and more versatile option will be to use plane polarising filters to hopefully reduce unwanted reflections.

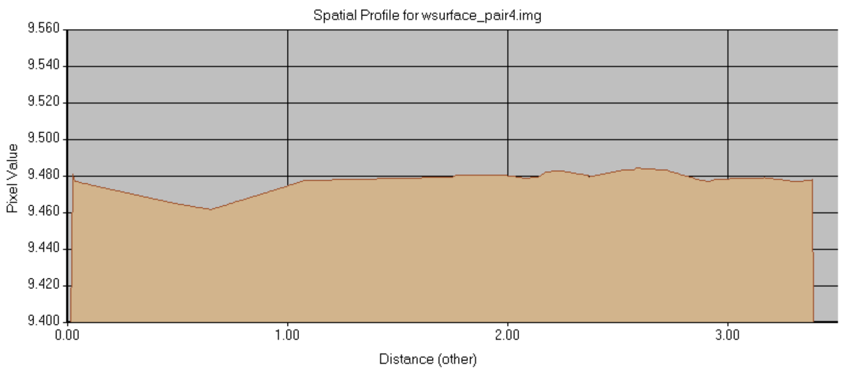

Figure 8. Exaggerated water surface profile in downstream direction (left)- real river

4.2 Flow modelling

As stated in the introduction, the key aim of the funded research project is to consider the role of vegetation on river flooding. Specifically, to quantify the impact of riparian vegetation on fluid flow in terms of turbulence, bed friction and water surface variation. One objective is to further develop existing three-dimensional numerical flow models to simulate flow, which currently rarely take into account the frictional effects of vegetative elements. In this context, a comprehensive data set comprising point velocities, boundary shear stresses and the free surface deformation and velocity is presently being acquired using diverse living vegetation specimens with different biomechanical properties and under both submerged and emergent conditions. It is thus expected to enhance, through empirical evidence, the current knowledge regarding the turbulent flow field in natural watercourses and riparian corridors and at the same time to derive improved parameters in a variety of simulations tools and conceptual models.

Spatial measurement is challenging and the major details and problems faced during data acquisition and processing has been given in previous sections. It is apparent that independently of the degree of automation achieved, such techniques are feasible to apply in both flume and field conditions. It is desirable to somehow strengthen the linkage between what is in its essence a remote sensing technology and hydraulic real world applications by enhancing and/or combining methods. In fact, there is a wide range of potential applications where the developed techniques can be applied, including: stage and discharge measurements for river basin management plans, CFD model validation or even more fundamental aquatic studies, among others.

Figures 7 and 8 show some initial outcomes. By surfacing the three-dimensional morphological data using conventional Delaunay triangulation, it is possible to generate water surface profiles through any desirable plane. For river flows, the principal direction of the plane needs obviously to be oriented towards the downstream direction. Figure 8 represents a downstream cross-sectional view which dissects a bush introduced into the flow in the river channel. (Note: Pixel value = elevation). It is apparent that surface elevation increases just before the bush at a distance of 2.5 m. This is a direct consequence of flow blockage caused by the vegetation which produces a local increase of the pressure field in the vicinity of the bush. There is also a depression as the flow dissipates around and behind the vegetation at a distance of approximately 0.7 m, which is consistent with the expected flow field created by such an obstacle.

Figure 7 represents the speed and direction of flow at the water surface, for one of the flume based image sets. The orthophoto suggest that the magnitude of these flow velocities do not vary spatially across and around the vegetation, at least for this particular test. This might indicate the presence of some structures on the water surface. Furthermore, independent velocity measurements derived using a 2D/3D side looking Acoustic Doppler Velocimetry (ADV) system (Vectrino), demonstrate that when compared to the approaching flow, longitudinal velocities increase outside the wake zone, and are compatible with the photogrammetric estimate.

4.3 Proposed future work

The measurement system described in this paper is evolving and further experimental work will hopefully refine procedures. Currently, use is just being made of two synchronised cameras but it has always been recognised that a third camera would provide valuable additional redundancy. A new triggering mechanism has been constructed to allow a third camera, a Nikon D7000. It is hoped that this should improve accuracy and allow processes to be further automated. However, achieving perfect synchronisation appears challenging, probably because slightly differing electronic systems associated with the two camera types, create differential time delays.

As discussed in Section 3.1, large and visually distinct seeds have been used in tests conducted to date. Utilising automated DEM generation methods have not proved practicable because of the lack of texture on the surface. Santel (2004) and de Vries *et al*., (2011) have reported success with automated DEM generation but it is probable that lighting conditions were uniquely suited. Han and Endreny (2014) describe the use of fine wax powder to create surface texture, which could be of use in the laboratory. This is an approach which could yield excellent results, particularly if Multi-View Stereo (MVS) DEM generation methods are utilised. This exact seeding material appears difficult to obtain currently, and so the search remains for a cheap, lightweight and easily distributable seeding material, which is also biodegradable. As this paper is published we are currently trying cork particles. Any other suggestions?

5. CONCLUSION

This paper has demonstrated the practicalities of deriving the three-dimensional surface topography and water surface velocity of a dynamic and flowing water surface. The technique is flexible and can be applied in both the flume and field environment. Commercial software appears able to automate many aspects of the photogrammetry-based solution, although both seeding and lighting, which consequently impact upon image quality, appears to play a critical control on the level of automation that can be achieved. Future proposed work will attempt to further automate the measurement procedures. Options include examining the potential of Multi-View Stereo by acquiring synchronised image triplets, but this will require identification and sourcing of an appropriate surface seeding material.

6. ACKNOWLEDGEMENTS

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