Budapest University of Technology and Economics
Department of Hydraulic and Water Resources Engineering

Analysis of UAV-based topography and river flow measurements

Drón-alapú áramlás- és domborzatfelmérés tesztelése

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By
Gabriella Lükő
BSc 3rd year in Civil Engineering

Advisor:
Dr. Sándor Baranya
Associate professor, Department of Hydraulic and Water Resources Engineering

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Abstract

Unmanned Aerial Vehicles (UAVs) are increasingly used in the field of engineering surveys. In river engineering, or in general, water resources engineering UAV based measurements have a huge potential. For instance, indirect measurements of the flow discharge using e.g. large-scale particle image velocimetry (LSPIV), particle tracking velocimetry (PTV), space-time image velocimetry (STIV) or radars became a real alternative for direct flow measurements. Besides flow detection, topographic surveys are also essential for river flow studies as the channel and floodplain geometry is the primary steering feature of the flow. UAVs will play an important role in this field too. The widely used laser based topographic survey method (LIDAR) can be deployed on UAVs, moreover, the Structure from Motion (SFM) method, which can use images taken by UAVs, might be a cost-efficient alternative to reveal the geometry of distinct objects in the river or on the floodplain.

In this study an overview will be given about the applicability of UAV based river flow measurements carried out in the past years in other countries. Next, attempts will be made to apply SFM to detect the geometry and prepare the digital model of different objects in the river Danube and the connecting floodplain based on video recordings from an UAV. Besides the geometric analysis the mapping of the flow will also be performed using UAV measurements and a quantitative assessment of the flow will be carried out. The measurements will be carried out using a simple, low-cost UAV, moreover, for all the data processing, open source, freely available software will be used leading to a cost-efficient methodology. The results of the UAV based measurements will be discussed and future research ideas will be outlined.

Tartalmi kivonat

A drónok használata egyre elterjedtebb napjainkban a különböző mérnöki felmérések során. A víz- és azon belül a folyógazdálkodás területén különösen nagy lehetőségek rejlenek a drónokkal végrehajtott mérésekben. Például az ún. Large-scale particle image velocimetry (LSPIV), Particle tracking velocimetry (PTV), Space-time image velocimetry (STIV) eljárások vagy a radaros sebességmérés valódi alternatívája lehet a hagyományos vízhozammérési eljárásoknak. A domborzati felmérések hasonlóan fontosak az áramlási viszonyok megértéséhez, mivel elsősorban a meder és a hullámtér geometriája határozza meg azokat. Ezen a területen is fontos szerepet fognak játszani a drónok. A most már széles körben használatos lézer alapú távérzékelés (LIDAR) mellett az ún. Sturcture from Motion (SFM) eljárás egy költséghatékony alternatíva lehet a mederben vagy a hullámtérben elhelyezkedő különböző műtárgyak geometriájának feltárásához, amihez drónnal készített felvételeket használhatunk.

A dolgozatomban áttekintem az elmúlt évek drón alapú áramlásmérésinek eredményeit, majd egy Dunai esttanulmányon keresztül kísérletet teszek az SFM alkalmazásával különböző műtárgyak és hullámtéri létesítmények digitális modelljének létrehozására saját drónnal készített videók felhasználásával. A geometriai felmérés mellett a drónfelvételek elemzésével számszerűsítem egy sarkantyú környezetében az áramlási viszonyokat. A mérésekhez egy egyszerű, olcsóbb kategóriás drónnal is elegendő minőségű eredményeket kaphatunk, valamint a domborzati és áramlásviszonyok előállításához használt programok is ingyenesen elérhetők, ezért összességében az eljárás költséghatékonynak nevezhető. Az dolgozatom végén értékelem a vizsgált módszerek alkalmazhatóságát és továbbfejlesztési javaslatokat fogalmazok meg.

1 Introduction

Unmanned Aerial Vehicles (UAVs) or drones officially mean aircrafts without pilots. The UAV flights can be operated under remote control by human operator or autonomously by onboard computers. The very first usage of UAVs was for military purposes, they have already been used in World War I. UAVs have huge potential in different kind of scientific utilizations as well as in engineering. The first applications of the laser-based (Light Detection and Ranging - LIDAR) and space-based radar and other photogrammetric techniques from UAVs appeared in the end of the 1990s. Today laser scanning is the most essential topography measurement method in the field of geodetic surveying. Also the usage of small hobby drones became increasingly popular in the past years. The selection of low-cost and user-friendly UAVs are nearly limitless. This means that pretty much everyone can control these flying vehicles (under legal conditions) and capture images from the air if a camera is mounted on the UAV. UAVs are getting higher potential in hydraulic and water resources engineering as well. For instance, indirect measurements of the river flow using e.g. large-scale particle image velocimetry (LSPIV), particle tracking velocimetry (PTV), space-time image velocimetry (STIV) or radars became a real alternative for direct flow measurements. These methods are based on analyzing video recordings of the water surface, for which the contribution of UAVs can be essential. There are already a couple of applications of UAV-based river flow measurements performed in the past few years in the US (e.g. Tauro et al., 2015a and 2015b; Blois et al., 2016), in Switzerland (e.g. Detert and Weitbrecht, 2015; Detert et al., 2016), or in Argentina (e.g. Patalano et al., 2015; Patalano and García, 2016). The referred studies, however, mainly focus on the measurement of flow discharge in rivers at different circumstances rather than revealing unique flow structures as will be demonstrated in this study.

This research aims to test and apply cost-effective and user-friendly tools for topography and river flow measurements using UAV-based images. As for the topography surveys, an attempt will be made to apply the so called structure from motion (SFM) method (Ullman, 1979), which computes 3D structures from the motion of the same points of the images taken from different positions of the objects to be assessed. The main benefit of the SFM method is its cost-efficiency compared to the widely used laser scanning (LIDAR) method, which is much more money and time-consuming. For instance, the SFM technique requires only one camera, and it takes only a few minutes to fly around even hundreds of square meters (depends on the altitude and the required level of detail) with a small UAV. Also, compared to the known problem of the laser scanning, that is the signal reflects from the trees and so the actual topography cannot be measured accurately, the UAVs are able to fly in non-dense forests. Another advance of the SFM method can be that free software might be used to create the 3D models of the objects to complete the DTM. The utilization of such a software is not straightforward, this is one important reason why this study has been carried out. Using the herein introduced software, the image processing is robust, even with using computers with average processor and memory capacity and poor graphic card. The resulted 3D geometries are essential when creating digital terrain models (DTM) for different investigations, such as Computational Fluid Dynamics (CFD) models. For further utilization of the SFM method introduced in this study, a protocol for the data process will also be produced. The testing of the SFM method will be demonstrated via a case study at the Danube River, where different objects in the river and the floodplain will be surveyed, such as a radial well, a section of a dyke and a groyne.

The other relevant part of this study is the analysis of river flow features based on images taken from an UAV. Although already a few promising studies can be found in the literature which deal with UAV based flow measurements (see above), none of them focused on revealing complex flow structures such as recirculation zones or eddy development at hydraulic structures. These features are indeed important from several aspects, e.g. for validating numerical models, understanding morphodynamic processes at obstacles or in mixing related problems. Here, the complex surface velocity distribution of the flow near a groyne has been analyzed, using the large-scale particle image velocimetry (LSPIV) (Fujita et al., 1998 and Muste et al., 2008) method. Furthermore, a pretty new flow measurement technique, the space-time image velocimetry (STIV) (Fujita et al., 2006), is tested in this study to compare and assess the capabilities of the image based velocimetry methods. The comparison of the two methods will be performed via a case study in a Norwegian river.

2 UAV-based topography measurements

In this chapter the Structure from Motion method will be introduced, and the testing and application of the method to create 3D models of river engineering objects.

2.1 Structure from Motion

The Structure from Motion (SFM) method is a new, cost-efficient alternative of the laser scanning. The SFM technique recreates a very detailed 3D structure from a series of 2D images taken with a camera moving along a path (Rootwelt, 2014). The algorithm takes as input a sequence of images and outputs a series of 3D points of the structure, called a point cloud. The basic interpretation of the method are shown on **Figure 1**, and there are many complex computational methods for solving this problem and produce the structure from the motion of the camera on the images.

$$\underbrace{\begin{bmatrix} \mathbf{I}_1 \\ \mathbf{I}_2 \\ \vdots \\ \mathbf{I}_f \end{bmatrix}}_{\textbf{Images}} = \underbrace{\begin{bmatrix} \mathbf{\Pi}_1 \\ \mathbf{\Pi}_2 \\ \vdots \\ \mathbf{\Pi}_f \end{bmatrix}}_{\textbf{Motion}} \underbrace{\begin{bmatrix} \mathbf{X}_1 & \mathbf{X}_2 & \cdots & \mathbf{X}_n \end{bmatrix}}_{\textbf{Structure}}$$

Figure 1. *Basics of the SFM technique.* I_1, I_2..I_f *are the individual images of the structure, which belong to same amount of camera positions* Π_1, Π_2.. Π_f. X_1, X_2.. X_n *are the created 3D points of the structure.*

The adaptation of general SFM approach follows these steps (Rootwelt, 2014):

1. Camera calibration

   Cameras have imperfections, such as lens distortions, non-square pixels and varying focal length. Cameras need to be calibrated as part of SFM and it needs to be done before the reconstruction starts.

2. Identify point of interest

   SFM outputs a series of points in 3D. These points need to be located in the 2D images before their 3D position can be found. The first step is to identify points that are easily recognized (**Figure 2**). These points are usually “corners” or other features that can be pinpointed in 2D.

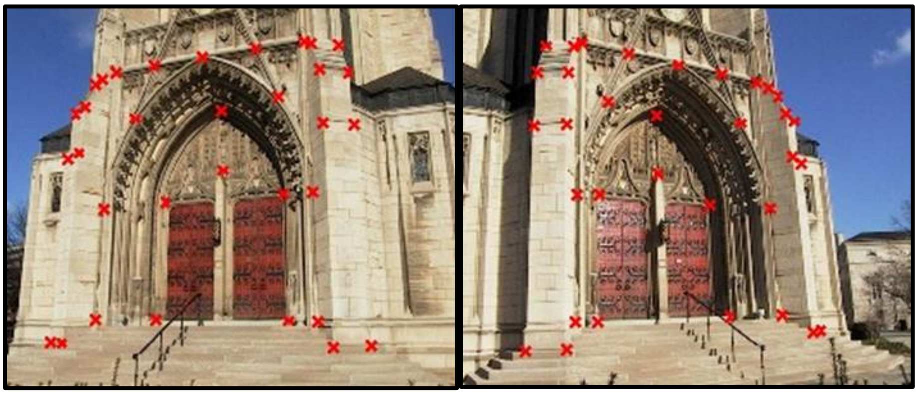


Figure 2. *Easily recognizable good feature points on images*

3. Track points

   Once the points of interest have been found in two images, they need to be matched. That means identifying which point in each image is actually the same 3D point. If the camera only moves a little bit, each point will be close to its match in the next image in the sequence.

4. Calculate camera movement

   Based on the movement of the tracked points from one image to another, the relative movement and rotation of the camera can be calculated, given each point correspondences. This encapsulated in the so called fundamental matrix F.

5. Triangulate points

   Once the relative positions of the two cameras are known, the 3D points can be triangulated. The basic principle is drawing a line from each camera center through the 2D points. These lines will intersect in the 3D point.

6. Bundle adjust

   Using two and two images is one way to get 3D information, but in SFM we generally have videos. Using information from multiply frames to get a more accurate estimation of the 3D points is called bundle adjustment.

The Structure from Motion method has been used for many different applications in the field of engineering in the past years. James and Robson (2012) used the method to estimate the erosion rate on a coastal cliff site in Lancashire, England and compared the results with the laser scanned model. Crandall et al. (2011) used an optimized large-scale SFM method to reconstruct Central Rome from images found on the internet. SFM was also used for remote sensing investigations by e.g. Niethammer (2011). Two landslides have been acquired in France and Austria, where the georeferenced model was used for digital terrain model (DTM) using open source software. Turner et al. (2012) used SFM method for creating a DTM as well. The testing of the SFM method in this study will be demonstrated via a case study at the Danube River, where different objects in the river and the floodplain will be surveyed, such as a radial well, a section of a dyke and a groyne.

2.2 Measurements

2.2.1 Applied UAV

In this study a DJI Phantom 3 Standard UAV has been deployed (**Figure 3.**). It is a low-cost, lightweight and user-friendly tool for the airborne SFM and LSPIV analysis. The main features of the Phantom 3 Standard are shown in **Table 1**. The UAV has factory-mounted HD camera with a gimbal. The vehicle can be remote controlled while using DJI Go App with a tablet or a smartphone. There are different flight settings and functions in the application, as well as at the UAV. The remote communicates with the pilot via the DJI Go interface. The camera position and the video recordings are also controlled from the tablet or phone. The flight routes are saved and available for further analysis on the SD card as well as the recorded videos in MOV file format.

Figure 3. *DJI Phantom 3 Standard /www.dji.com/*

Diagonal size (excluding propellers)	350 mm
Total weight (including the camera).	1216 g
Intelligent flight battery	LiPo 4S (4480 mAh, 15.2 V)
Hovering time	25 min

Table 1. *The main features of the DJI Phantom 3 Standard*

The drone was used to record the area for the 3D terrain model. Previous UAV pilot course and flight tests have been carried out (**Figure 4**) to gain experiences of the drone control. There are several important tasks which are responsible for the safety of the flight. Having an insurance and a permission for the used airspace (bookings can be done online), also a permission from Water Directorate for doing measurements on their property have to be done. It is essential to be aware of basic UAV regulations, such as flying close to people is not allowed. Valid UAV pilot license is necessary to use drones.

Figure 4. *UAV flight practice*

2.2.2 Field measurement

The measurement campaign took place in the Island of Szentendre at the right bank of the Váci branch of the Danube River at rkm 1675 on the 16th of September 2016 (**Figure 5**). The weather conditions were sunny and a little windy, the temperature was around 25 °C.

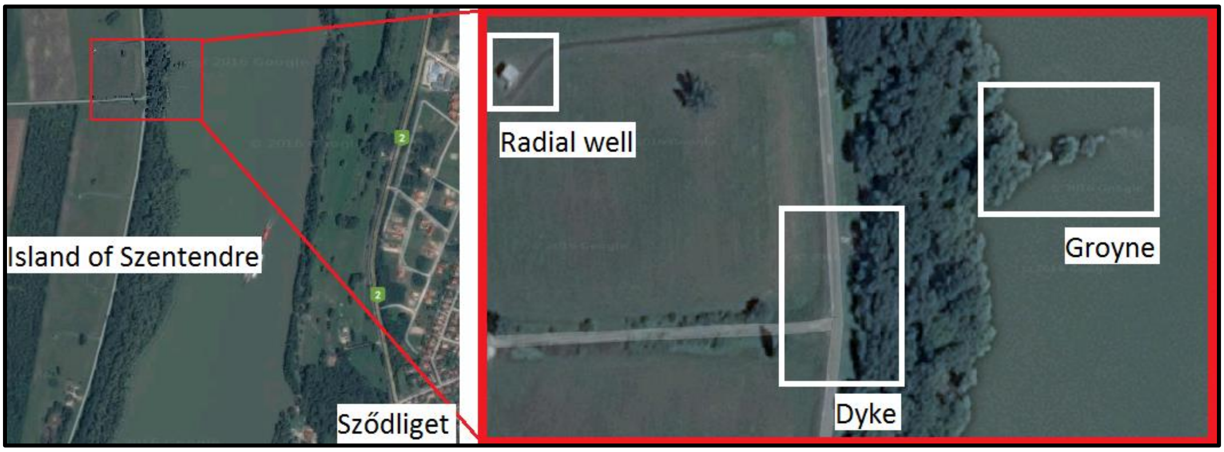


Figure 5. *Measurement field*

2.2.3 Measurement method

There were 3 flights performed. In order to test the applicability of the SFM method different objects from the river and floodplain were recorded:

- a building of a radial well,
- a dyke,
- and a groyne.

During a survey the UAV flies around the object slowly. The vehicle is remote controlled by the pilot and another person controlled the application from the tablet, starts/finishes the recordings and controls the camera position (forward/downward).

The measurement method requires reference points (easily visible points on the recorded videos with known geographical coordinates), so an RTK-GPS has been used to measure the real X, Y, Z coordinates of the objects (here, the Hungarian Coordinate system, EOV, was applied). The reference points must be clearly identifiable on the UAV recordings.

2.2.4 Image processing

To get the complete georeferenced 3D point cloud out of the recorded video, we used four different open-source software in this study:

- ffmpeg (https://ffmpeg.org/ffmpeg.html)
- VirtualDub (http://www.virtualdub.org/virtualdub_docs.html)
- VisualSFM (http://ccwu.me/vsfm/doc.html)
- Meshlab (http://www.cyi.ac.cy/system/files/MeshLab%20Documentation1.pdf)

Ffmpeg software is responsible for converting and cutting the raw video files. The program can be run from the command line. *VirtualDub* is used to export a sequence of images from the video with necessary frame rate settings. The *VisualSFM* software is used to create the 3D point cloud itself, seeks for the good feature points and matches the images with the same points. It calculates the camera positions and creates the point cloud from the camera motion in a random non-georeferenced coordinate system, where the 3D structure is already recognizable in a good quality. The *Meshlab* software is used to clean up the trees and other inappropriate objects on the point cloud and creates a georeferenced point cloud using the real coordinates of the ground reference points. Since all the software applied here are academic, there are several bottlenecks when applying them. During the tests carried out in this study a lot of useful experiences have been gained how to overcome the limitations and issues of the programs. In order to provide a straightforward way for future SFM applications a detailed image processing protocol has been created which defines the process step by step from the video recording until getting the 3D point cloud of the study area. The protocol can be found in the Appendix of this study.

2.3 Results

2.3.1 Radial well

As a first test of the SFM method the building of a radial well, located on the floodplain, was recorded by the UAV. A raw image extracted from the video recording can be seen in **Figure 6**. The result of the dense point cloud of the radial well in *VisualSFM* is shown in **Figure 7**. The detailed 3D model was built up from 219 images. The point cloud together with the 219 different camera positions are shown in **Figure 8**. The model has 66048 vertices. The image processing took about 1 hour without any further cleaning as no dense vegetation could be found nearby the building. At this point no georeferencing was applied since only the applicability of the image processing tool was tested.

Figure 6. *Raw image of the radial well from the UAV*

Figure 7. *Raw 3D dense point cloud of the radial well from different views in VisualSFM*

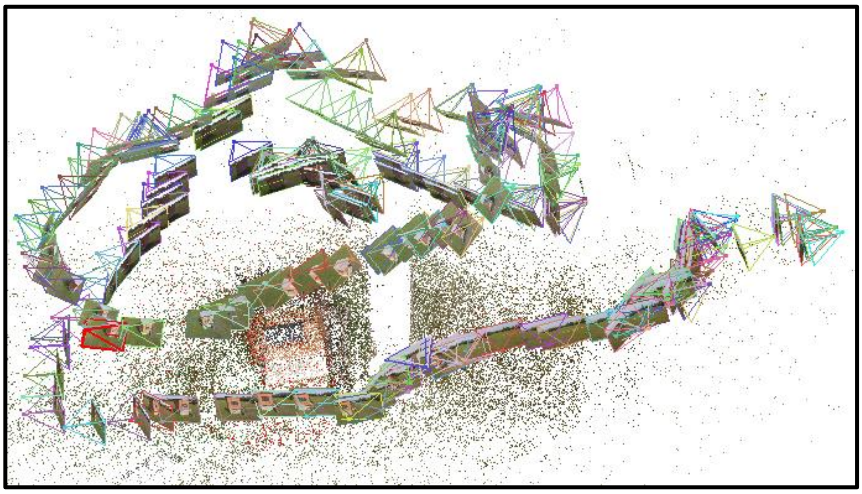


Figure 8. *Calculated camera positions around the point cloud of the radial well in VisualSFM*

The SFM method reconstructed the building of the radial well in a surprisingly good quality. It is visible that the grass has less points further away, where the images had less information about it. Some light blue points also can be seen next to the building, which are calculation problems from the sky behind the building, but it could easily be removed posteriorly. Probably the quality of the 3D model could be even more improved flying slower with the UAV or simply using higher time resolution at the video processing (more frames per second), or the UAV would fly around the object from even more different altitudes as well. Processing more images will obviously increase the processing time significantly though which must be considered when surveying larger areas.

2.3.2 Dyke

Dykes or levees are elongated structures built parallel to the river, which protect the floodplains against floods. Accurate information about the geometry of these structures is essential when investigating e.g. flood situations, influence of dyke breaches, geotechnical behavior of dykes, or planning flood localization. To reveal the feasibility of SFM based reconstruction of dyke geometry, video survey of the dyke at the study site was also performed. A raw image of the dyke extracted from the video is shown in **Figure 9**. The result of the dense point cloud of the dyke in *VisualSFM* is shown in **Figure 10**. The 3D model is built up from 356 images and has 674420 vertices. The image processing took about 3 hours in *VisualSFM*.

Figure 9. *Raw image of the dyke from the UAV*

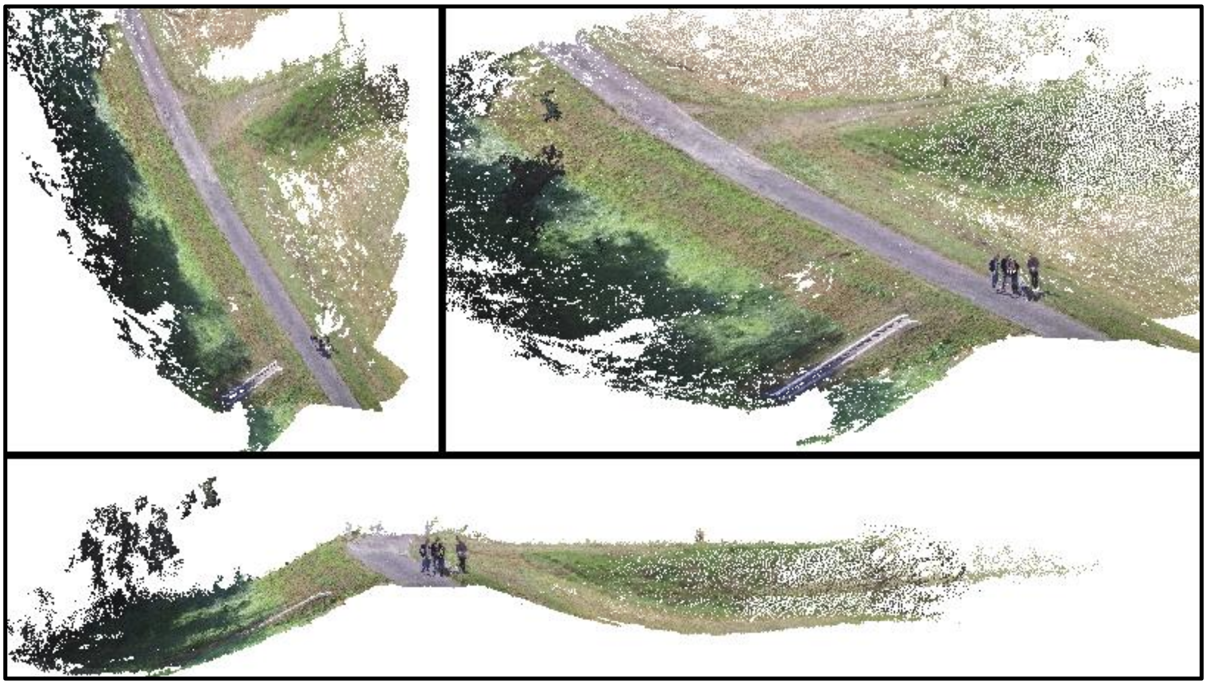


Figure 10. *Raw 3D dense point cloud of the dyke from different views in VisualSFM*

Considering the possible later utilization of the built 3D objects (e.g. inserting it to existing DTM, applying for CFD modeling) the cleaning of the point clouds is a crucial step in the post-processing procedure. This means that points representing bushes, trees, even people on the images have to be removed before creating the 3D model. This can only be done manually, which makes the procedure slower, however, the deleting of the clearly not ground points is straightforward. After cleaning the inappropriate vertices (trees, people, etc.) from the point cloud, the axis-fixed, georeferenced 3D mesh is shown in **Figure 11**. The 3D surface from the point cloud, visualized in the Tecplot software, is shown in **Figure 12**. These additional edits took another 20 minutes in this case.

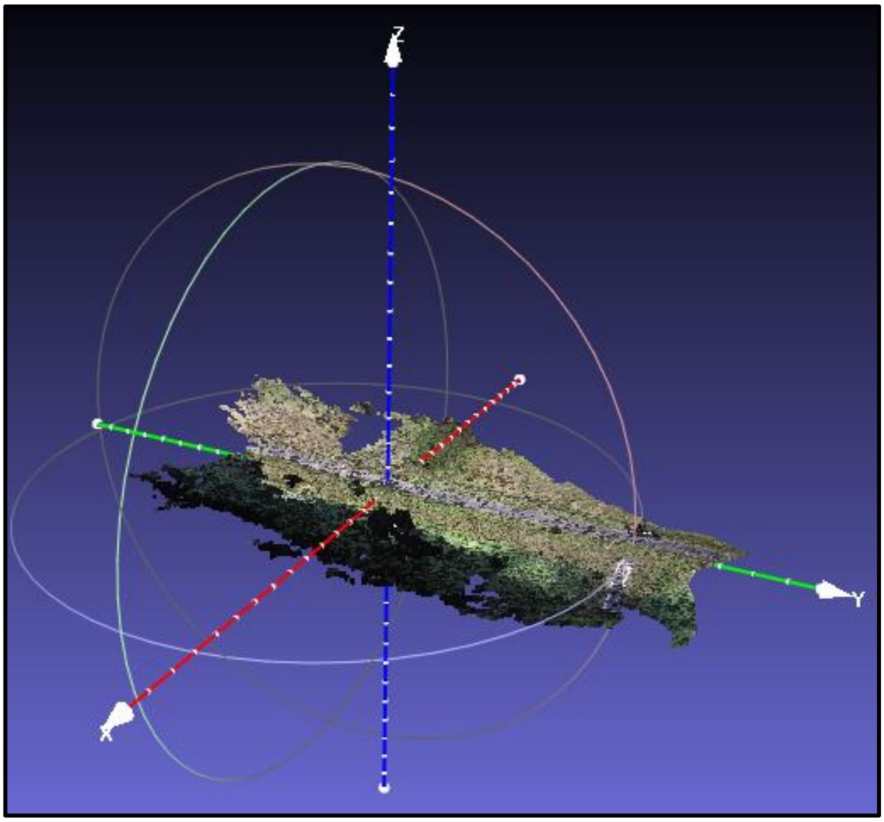


Figure 11. *Cleaned and axis-fixed 3D mesh of the dyke in Meshlab*

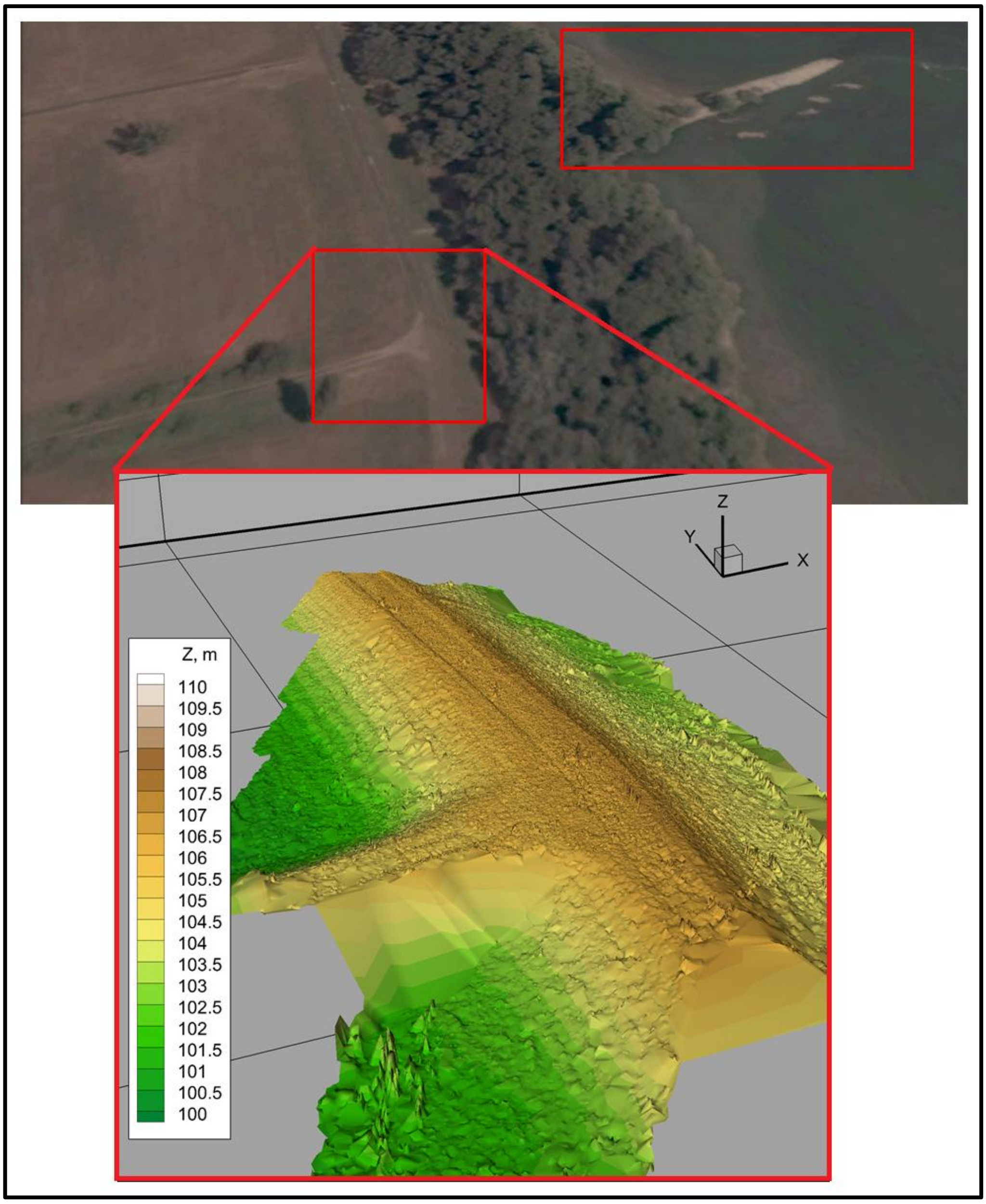


Figure 12. *Cleaned and georeferenced surface of the dyke visualized in Tecplot*

2.3.3 Groyne

Groynes are river engineering structures built at the banks perpendicular to the main flow direction. The aim of these structures is to narrow the navigational channel and thus to let the river itself to maintain its sufficiently deep river bed. The knowledge of precise geometrical data of these structures is very important when analyzing the water flow or morphodynamic processes in a regulated river. The geometry of the river engineering structures is of major importance when using CFD models to simulate the above mentioned processes. Due to the simplicity of the drone based surveys an attempt was made to build up the 3D model of a groyne at the study reach. At this point it is important to note that submerged objects can hardly or not be detected and processed by this method. Therefore, in order to measure the possibly largest part of the structure the field survey has to be carried out during low water regime. During the herein introduced measurements the flow was reasonably low (the flow discharge was around 700 m^3/s). The raw image of the groyne from the UAV is shown in **Figure 13**. The result of the dense point cloud of the groyne in *VisualSFM* is shown in **Figure 14**. The 3D model is made from 178 images and has 35151 vertexes. The image processing took less than 1 hour.

Figure 13. *Raw image of the groyne from the UAV*

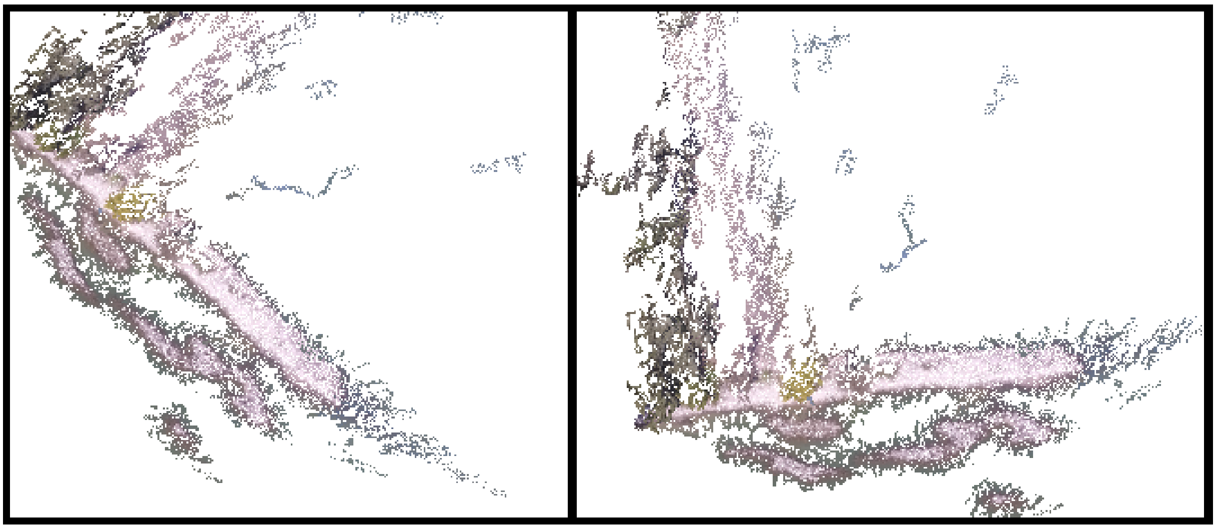


Figure 14. *Raw 3D dense point cloud of the groyne from different perspectives in VisualSFM*

After cleaning up the inappropriate vertices (trees, water, etc.) just like in the previous step, the axis-fixed, georeferenced 3D mesh is shown in **Figure 15**. The 3D surface from the point cloud can be visualized in Tecplot, shown in **Figure 16**.

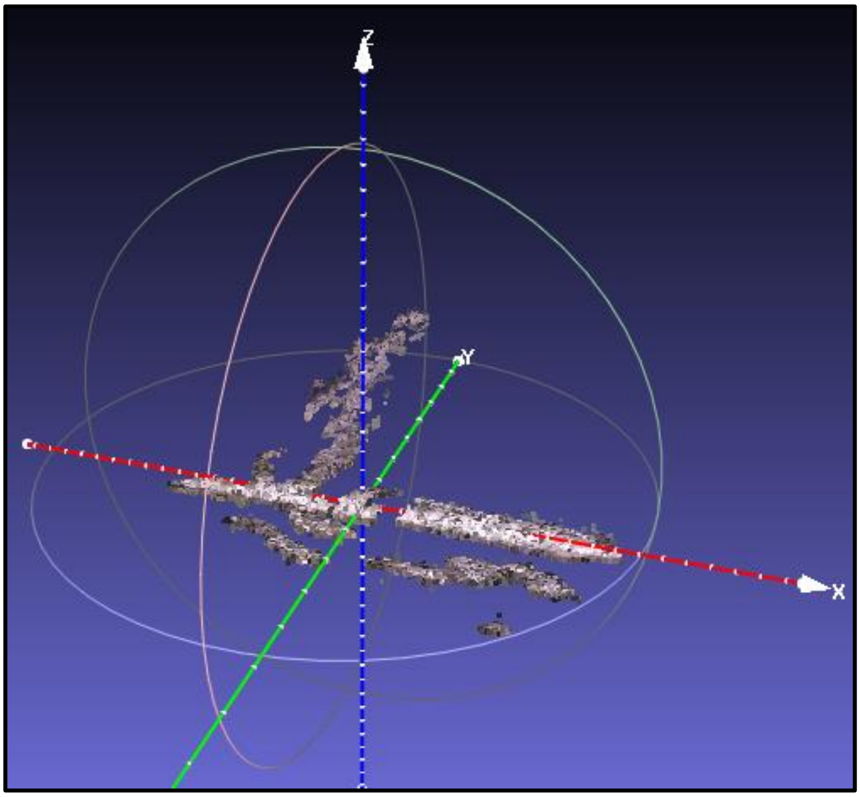


Figure 15. *Cleaned and axis-fixed 3D mesh of the groyne in Meshlab*

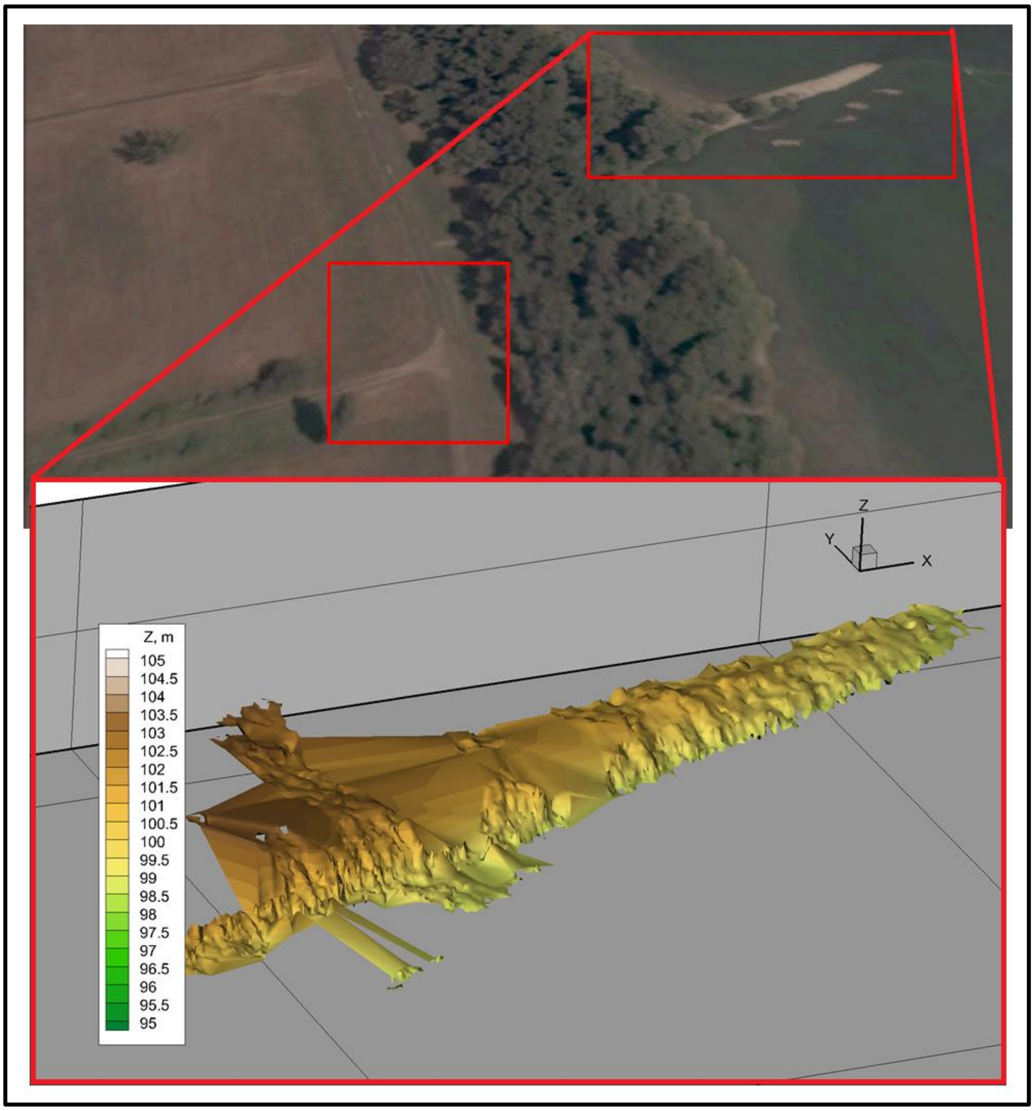


Figure 16. *Cleaned and georeferenced surface of the groyne in Tecplot*

The most important experiences of the topography measurements are that a couple of hundred square meters can be recorded with the UAV within 2-10 minutes, depending on the experience of the pilot. At least 3-4 ground reference points need to be measured with, for instance, an RTK GPS. The image processing takes a few hours, but actually only needs 4 mouse clicks with the *VisualSFM* software. The inappropriate objects (from the DTM point of view), like trees can be removed and the model can be georeferenced in *Meshlab* posteriorly, which, in this case, took only about several minutes for the groyne or the dyke. Extending the topographic surveys to large areas can, however, increase the time demand of the manual phases of the image processing procedure. Another, important advantage of the UAV-based SFM method, compared to LIDAR performed from airplanes, that the UAV can fly very low (at the level of the trees) along the river bank, and able to record some parts of the ground while the trees themselves will be removed with a very little effort. So the method can get information about the geometry of the river bank quite easily, while the LIDAR vehicle cannot fly so low and removing trees takes a very long time. The whole SFM procedure or the post processing cannot be automatized though, but still it is a fast and more cost-efficient alternative and, as shown in the previous points, results in very detailed 3D information about the study area. The next step of developing the UAV-based SFM tool would be creating 3D models in larger scale as well. The method is able to reconstruct the digital model of hundreds of square kilometer sized objects too, in a faster and cheaper way compared to other survey methods. However, the SFM processing time might increase roughly exponentially to the number of images, and the cleaning of the raw point clouds is also more challenging and slower when working with large areas. This means that the most efficient way to create large scale topographic models using SFM can most probably achieved by merging smaller models. From practical point of view it is worth to note that several *VisualSFM* windows can be run parallel, which makes the post-processing even easier and faster. The processor and memory capacities of the computer could set limits though. The accuracy of the model can be checked in several ways. The easiest way is to check the calculated coordinates of the reference points on the model and compare it to the original real coordinates. Another way could be the comparison of the calculated point clouds with detailed GPS or LIDAR measurement of the object. As to the data collection, one has to consider that flying above the water surface might be more dangerous, as UAVs usually do not survive falling into the water. Also, it has to be taken into account that locating reference points when recording videos above the water is more challenging. In this study the necessary number of reference points was defined on the groyne itself and along the river bank.

2.4 DTM application

As a typical final application of the geometric data provided by the SFM method, the reconstructed models of the dyke and the groyne have been inserted into an existing DTM. The DTM of a 10 km long reach of the Danube River near Sződliget was recently built up for a numerical modelling study (Fleit, 2014b). The geometric data used in the referred study to create to computational mesh for the numerical model was much less detailed compared to the herein introduced SFM based data (for instance, the groyne geometry was measured with GPS at 10-15 points). The uncertainty of the geometry can easily lead to inaccurate results of the flow simulations especially in regions where complex geometry presents. Local refinement of the geometry of the computational mesh can be performed using the much detailed, georeferenced UAV-based 3D models. This has been done here, adding the geometry of the dyke and the groyne to the already existing DTM (**Figure 17**). Similarly to this test application, the procedure could be done for the whole study reach using UAV-measurements with SFM processing, which would yield a more accurate topography model.

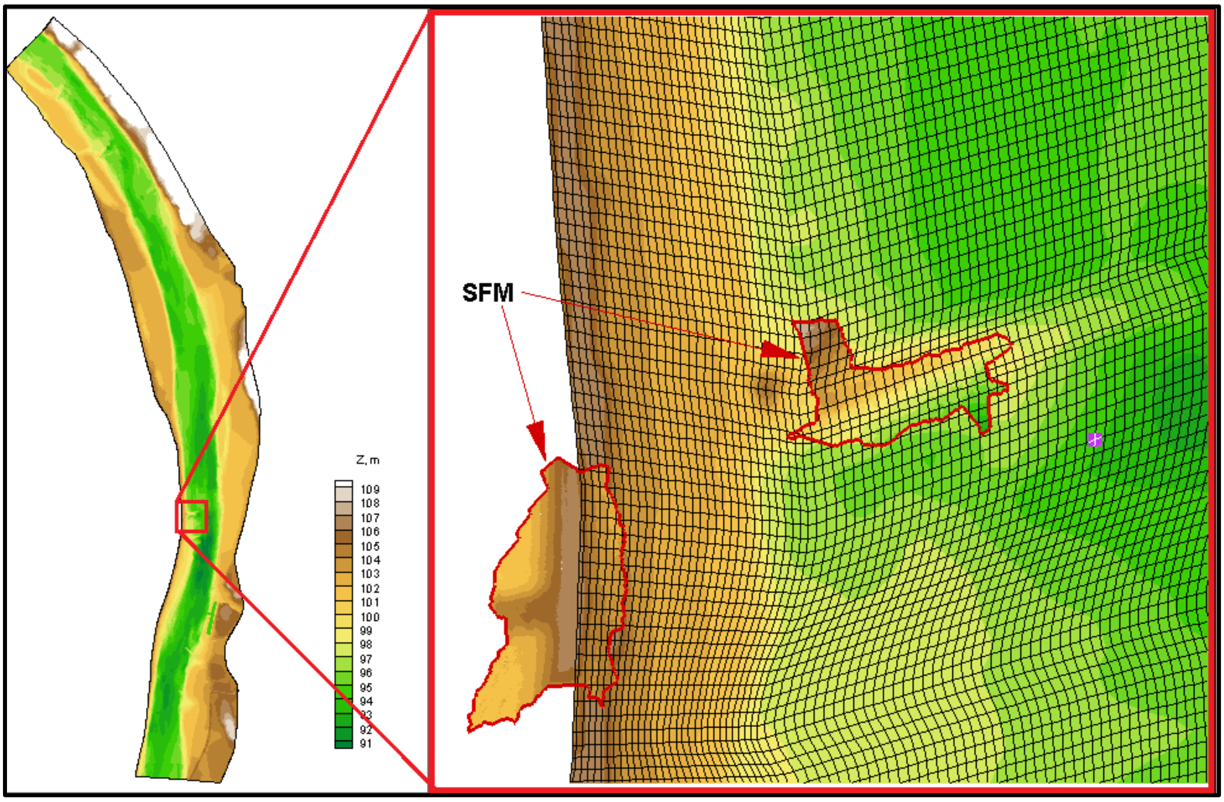


Figure 17. *SFM-made 3D objects added to DTM in SMS software*

3 UAV-based river flow measurements

Indirect river flow measurement methods seem to be a new alternative of other conventional measurement techniques (such as current meter, acoustic devices, measuring weirs and flumes, etc.). Measurements of the flow in small rivers and streams are still challenging, and sometimes the indirect methods can be more suitable, in such cases as flash floods, too shallow flows, or when the rating curves are uncertain.

There are a few already existing image-based river flow measurement techniques, such as the large-scale particle image velocimetry (LSPIV), space-time image velocimetry (STIV) or particle tracking velocimetry (PTV). The LSPIV and STIV use the Eulerian specification of the flow field, and these methods focus on specific locations in the space through which the fluid flows as time passes. A few recent UAV and non-UAV based LSPIV applications can already be found from the past years as well as STIV applications. These studies, however, mainly focus on the measurement of flow discharge in rivers at different circumstances rather than revealing unique flow structures as will be demonstrated here. The PTV method uses the Lagrangian specification of the flow field, looking at fluid motion where the observer follows an individual fluid parcel as it moves through space and time. As to the knowledge of the author no PTV application has yet been done based on UAV surveys. On a longer term, a potential utilization of UAV-based videos will be to track tracers in the river and analyze the space-time behavior of the flow file in a Lagrangian way, but in this study we focus on the LSPIV and STIV testing.

3.1 Large-scale particle image velocimetry (LSPIV)

3.1.1 Methodology and relevant literature

Large-Scale Particle Image Velocimetry (LSPIV) is a novel way to measure streamflow (Muste et al., 2008). The method (**Figure 15**) is based on recording the water surface with a video camera, a transformation of the images into a truly 2D coordinate system, and the image processing. Ground reference points (GRPs) (**Figure 16**) are defined on the raw image and the real coordinates of the points needs to be added so the transformation can be done. The results are instantaneous velocity vector fields of the free surface. The method is based on the tracking of patches on the free surface, therefore the presence of some sort of tracers is essential.

Figure 15. *LSPIV measurement sequence*

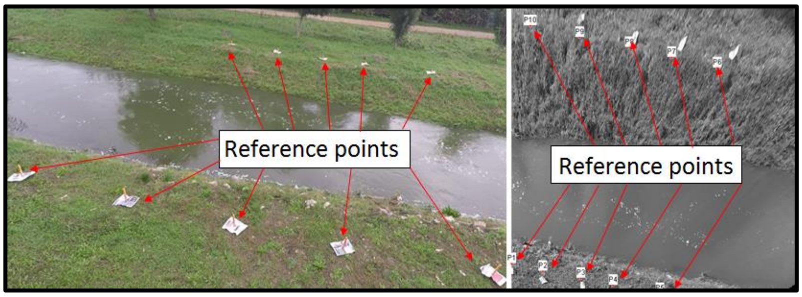


Figure 16. *Ground reference points (GRPs)*

The procedure is performed to consecutive image pairs. An Interrogation Area (IA) is defined in the first image, then a usually larger Searching Area (SA) is defined in the second image (**Figure 17**). Similarity index (cross-correlation coefficient, *R*) is calculated for each IA to find similar patterns within the SA. The highest similarity index shows the displacement of the pattern. Since the time difference between the two images is known, a velocity vector can be given.

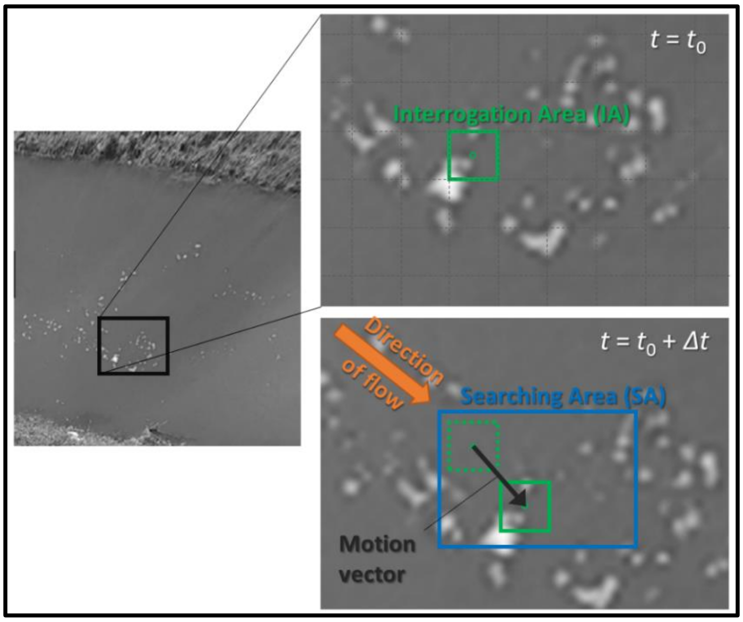


Figure 17. *Definition of interrogation area (IA) and searching area (SA)*

Performing the method over the whole image, a series of 2D instantaneous velocity vector field can be provided. Based on the instantaneous velocity fields, a time-averaged 2D velocity field can be created. If this vector field is averaged over the entire image, a space- and time averaged velocity vector is given, which we call index velocity (**Figure 18**). The discharge (Q) is calculated using the $Q = v \cdot A$ continuity equation, where A is the wetted area and v is the cross-section averaged velocity. The latter is derived from the index velocity (v_i) once the relationship between v *and* v_i has been established. The wetted area can be estimated from a known water stage (H) - wetted area (A) relationship.

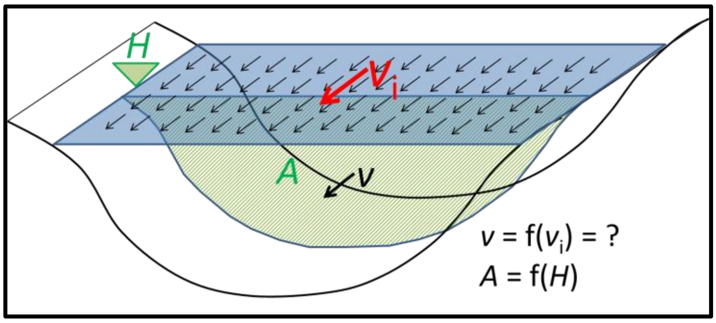


Figure 18. *Index velocity in the surface velocity field*

In this study, even though the original purpose of LSPIV is the discharge estimation, we focus on the assessment of unique flow features in the river. Several tests has been performed, and the results showed that the method works reliably and stable at adequate conditions (in the presence of tracers, repeated calibration, etc.). The LSPIV method works at different kind of applications as well.

- The location of the video camera is optional and not permanent, the real coordinates of the reference points need to be measured. The LSPIV procedure cannot be automatized. Simple and cost-effective way, but the post processing takes long sometimes.
- The traditional fix position LSPIV, where the reference points need to be measured only once. At this point the method can be automatized online if using an IP camera. The surface velocity or the discharge data is calculated by a frame program, which runs the steps of the LSPIV process automatically. Tests have shown that this system works stable and reliable. This way real-time river flow data is generated automatically, which saves a lot of both time and work.
- The video camera is mounted on an UAV. The video can be recorded from the UAV's camera orthogonal to the surface, so the image orthorectification is not essentially necessary. Many measurement systems can be calibrated using one UAV.

Using either ways of the LSPIV method, the repeated calibration and the presence of the tracers are essential.

There are a couple of UAV-based LSPIV applications performed in the past years. Tauro et al. (2015a) developed a lightweight quadrotor for the LSPIV. A gimbal was applied to the vehicle for the camera lens to be orthogonal to the water surface preventing the image orthorectification. Field experiments showed that the vehicle is able to stably hover an area of 1 * 1 m^2 for 4 minutes with a payload of 532 g. The UAV-based LSPIV is demonstrated through tests in an outdoor laboratory and over a natural stream. A detailed sensitivity analysis has been done by the same researchers (Tauro et al., 2015b). They analyze the effect of tracers' visibility, and it is assessed through the index $Z = N_0/N_{TOT}$, where N_0 indicates the number of nodes presenting velocity values less or equal to 10 % the average velocity in the entire time-averaged map, and N_{TOT} is the total number of nodes is the map. Also analyzed the stability of the experimental platform, and it is assessed through the index $D = N_d/N_{TOT}$, where N_d refers to the number of nodes presenting negative velocity values, that is, vectors in the opposite direction of flow. In case of fixed configurations, the *D* index is found to be equal to zero. Structural similarity index (*SSIM*) is largely used in image analysis to quantify differences between images in terms of luminance, contrast, and structure. *SSIM* is computed on the time-averaged velocity maps obtained for each experimental replicate. Also, the maximum velocity values were analyzed, so the velocity range values for cross-sections. Patalano et al. (2015) applied the flying LSPIV because of the wide rivers at flood events and too high angles for the fixed LSPIV**.** The tests have been done during a river flood of the Suquia River. Accurate velocity measurements were also been carried out at the same time with an acoustic Doppler current profiler (ADCP). The UAV was equipped with a camera (recording 30 frames per second), and it was placed on a gimbal that absorbs vibrations of the vehicle. The discharge measured with the LSPIV was 73 m^3/s versus 74 m^3/s with ADCP, which represents a difference of 1.35 %. The same researchers introduced a new toolbox (RIVeR) used in rivers, channels and also large physical models (Patalano and García, 2016). The toolbox uses the results from conventional 2D large-scale image-based flow velocimetry techniques orthorectifying them instead of orthorectifying the images first, which reduce dramatically the computational cost. RIVeR is fully operational and has already been used in many applications with extreme conditions such as stream gauging during flash-flood events and low water level. Detert and Weitbrecht (2015) proved the applicability of a low-cost airborne velocimetry system to measure large-scale velocity field. The measurement equipment consisted of an ultra-light action-cam and a ready-to-fly low-cost quadcopter. Video recordings were performed from heights between 45-74 m covering a total length of 310 m, while spruce chips were added as tracer particles. Each lens-corrected frame was automatically orthorectified to riparian ground reference points. The positional error of each point was computer to be within 0.17-0.39 m, so that the magnitude of the related descaling error was below ±2%, and the error of apparent found velocity is approximately 0.03 m/s. These values describe the uncertainty added to the subsequently calculated particle image velocity profiles measured by ADCP indicates that the proposed new type of velocimetry system is capable of measuring with relatively high accuracy. Also an optimized application of a low-cost airborne surface velocity system has been developed (Detert et al., 2016). At Surb Creek, Switzerland, on a reach length of 650 m surveying flights and PIV analysis had been performed. The remaining velocity error due to orthorectification for the example given was estimated to <0.01 m/s, and the total error was estimated to be <0.1 m/s. The raster resolution was 0.5*0.5 m with 50% overlap. The optimized system was capable to provide flow fields with high resolution in time and space, a high potential tool for data acquisition in the field. There is a specifically-developed UAV system to remotely and safely gain high-resolution images of the water surface (Blois et al., 2016). It presents details of a Scale Invariant Feature Transform (SIFT) that permits accurate rectification of the images. These data are key to informing and calibrating predictive tools that can reconstruct potential emergency scenarios. They discuss the concept and technology employed to render these measurement systems effective, and provide examples of applications that show the fidelity of the data that can be extracted from aerial images, and thus the vast potential of this technology. Several helicopter based measurements were also performed in the past years (e.g. Detert and Weitbrecht, 2014; Fujita and Hino, 2003; Fujita and Kunita, 2011). These prove the robustness of the aerial LSPIV methods again, but the helicopters cannot be included in the group of cheap or cost-efficient measurements.

The goal of this part of the study was to test the capabilities of UAV based LSPIV to reveal and analyze unique flow patterns at complex situations, around hydraulic structures in this case. Such information could provide essential validation data for numerical hydrodynamic models and can contribute to a better understanding of morphodynamic and mixing processes around obstacles.

3.1.2 Measurements and results

As shown in the in the overview (Chapter 3.1.1) there are a number of papers about video-based river flow measurements done from UAVs, where image stabilization had been done to reduce the effect of the vehicle's vibration to the images. In this case, however, using the Phantom 3 Standard UAV, the video was found to be very smooth due to its quality gimbal-work under normal weather conditions which will be discussed below. The UAV flights were done in GPS-mode, which means the vehicle is keeping its position stable while hovering and not being remote controlled to move (basically when the remote is not being touched). This means in windy, but not too cloudy weather, when the wind keeps trying to blow away the UAV, the GPS makes the vehicle fly back right away. The accuracy of the GPS coordinates depends on the number of available satellites, but it's between 5 and 10 cm. Since the UAV moves the same amount towards each direction while averaging for the measurement time, image stabilization was not necessary in this case.

Flow conditions around river engineering structures, such as groynes, are more complex than in prismatic channels. Groynes, as introduced above, are linear objects perpendicular to the main flow direction, built at the bank of the rivers to narrow the channel. The elevation of the crest of the groynes is generally built to the mean water level. This means that during high water the structure is submerged and has much less impact on the flow field than during low water regimes. In the latter case flow acceleration occurs at the tip of the obstacle, which results in a flow separation and slow recirculating flow on the downstream side of the groyne. These complex flow structures can be detected using modern acoustic measurement methods, however, instantaneous flow pattern over a larger area cannot be detected with a single device. Acoustic Doppler current profiler (ADCP) measurements can be done from a moving boat, which provide instantaneous vertical velocity distributions (e.g. Fleit, 2013).

The video-based velocimetry can be an alternative technique to direct measurements of the flow features if well trackable tracers present on the free surface. In such a case the more time and money demanding field surveys made from vessels can be substituted with drone-based video recordings. It must be considered that only surface flow patterns can be captured though. In this study the foam, resulted by the flow around the groyne, was detected as the tracers for the method. Reference points can be placed on the river bank or the groynes as well. Flow pattern analysis on two scales was performed: i) on a larger scale for the area between the two groynes located in the study area, meaning a streamwise distance of 300 m and a lateral width of 100 m; ii) on a finer scale focusing directly on the vortices developed at the tip of the groyne.

The first measurement campaign took place at the Danube River on the Island of Szentendre on the 16th of September 2016 along with the topography measurements. The discharge of the river section was 700 m^3/s that day, which is low water regime. The UAV was remote controlled from the bank of the Danube River, the video was recorded at the top of the groyne from 50 m above the ground and the camera was orthogonal to the water surface as it is shown in **Figure 19**. The LSPIV method worked robustly on the UAV-based images but it was found that due to the vertical position of the camera the size of the captured region is very limited and allows only fine scale (eddy scale) flow analysis. Consequently, the UAV needs to record the videos rather from a perspective view. Also, an important experience was that the UAV cannot fly higher than 70 m because of the weak remote control signal. Indeed, after assessing the videos from the first measurement campaign it was clear that another measurement campaign was needed. The advantage of the vertical position of the camera is that directly 2D undistorted images are provided by the video. Although, the perspective view is also manageable as the herein used FUDAA-LSPIV software (Le Coz et al, 2013) is capable to perform the so called orthorectification process, which accounts for removing the perspective view resulted distortion from the images (see e.g. Lükő and Baranya, 2016).

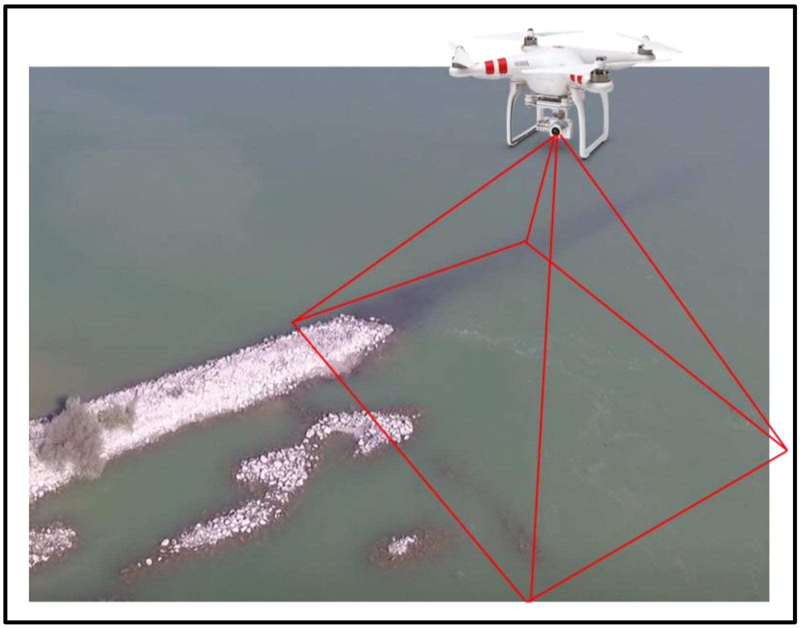


Figure 19. *The captured water surface at the first measurement campaign*

The second measurement campaign was performed on the 7th of October 2016, when the discharge was 1340 m^3/s at the same spot, which is rather medium water regime. The videos from perspective view were recorded successfully. The take off and the landing were managed from the groyne, as well as the remote controlling. The videos were taken from 50 m above the ground and 40 m further upstream of the groyne. Six reference points were measured with RTK-GPS and used for the image orthorectification. The camera view as well as the measurement field can be seen in **Figure 20**.

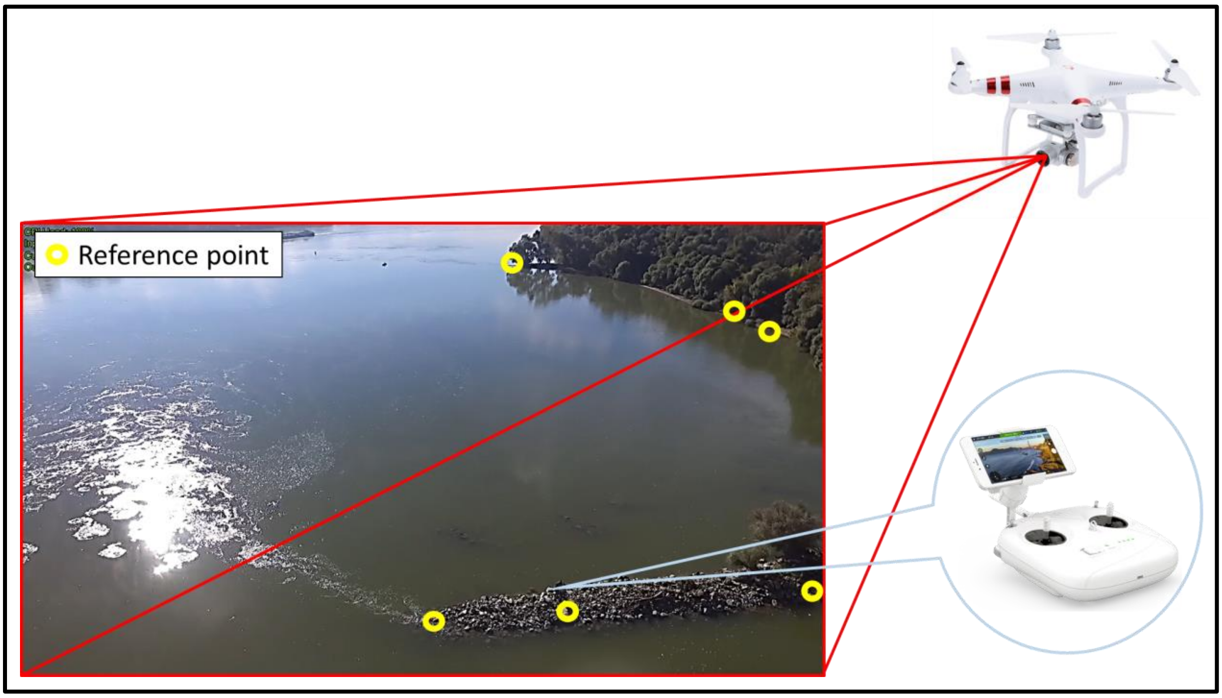


Figure 20. *Measurement field for the LSPIV*

The image processing and a detailed sensitivity analysis have been done the same way as it is introduced in a recent study (Lükő, 2015) using the FUDAA-LSPIV software. The following parameters of the LSPIV method were studied within the sensitivity analysis: image resolution (pixel size), interrogation area (IA) size, correlation coefficient (R) filtering and the length of the video. The specified parameter values after the sensitivity analysis:

- frame rate = 5 fps
- pixel size, 1 pixel = 0.05 x 0.05 m
- Interrogation area size, IA = 60 pixel
- correlation coefficient, R = 0.6
- length of the video, T = 30 s

The calculated time-averaged surface velocity field near the groyne is shown in **Figure 21** (note that the view is perspective). The low correlation coefficient value was chosen because of the light refraction, using higher value would have not provided such realistic velocity distribution. The local flow acceleration at the tip of the groyne can be well observed together with the flow steering effect of the structure. Downstream of the flow contraction the maximum velocity decreases and the flow becomes parallel with the main flow direction, i.e. the influence of the structure weakens. The highest flow velocities reach 1.4 m/s, whereas in the low flow zone between the two groynes can be characterized with close to zero velocities. The LSPIV method found less vectors as it gets further away from the camera and the groyne. This is resulted by different issues: i) there are less moving tracers on the free surface and the LSPIV method becomes less reliable; ii) the flow velocities are decreasing which causes inaccuracy in the LSPIV method; iii) the distortion of the image is higher in that farther zone, and the inaccuracy resulted by the orthorectification is higher. Considering all these limitations the vector field shows reliable information of the flow pattern closer to the groyne and further improvement is needed to get reliable information on a larger scale, e.g. recording the videos from a higher view with less distortion, which could be performed with a more advanced UAV (a six-rotor one, for instance). Nevertheless, the flow recirculation pattern can also be quite well observed resulted by the strong shear layer between the high and low velocity zones.

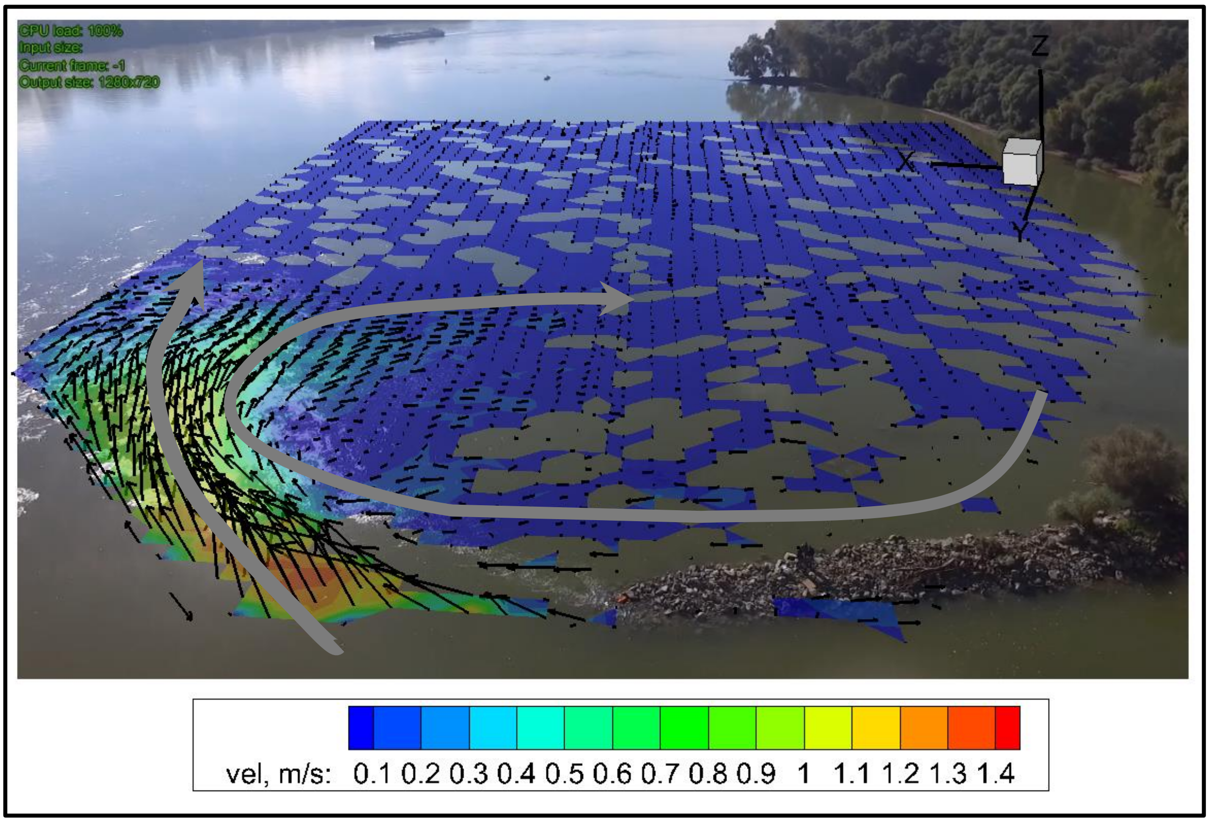


Figure 21. *Surface velocity distribution near the groynes from UAV-based LSPIV measurements (perspective view)*

In order to assess the velocity field resulted by the UAV based imaging, measured flow velocities from a recent measurement campaign, carried out with moving boat ADCP, are shown (**Figure 22**) (Fleit, 2013). The water regime was similar, the flow discharge was around 1340 m^3/s. The velocities around the groyne show a similar behavior. The highest velocities are around 1.2 m/s, which matches the LSPIV results. Note that the boat could not get directly to the tip of the groyne as the UAV, so this region was not measured accurately. The flow recirculation was captured with the ADCP too, moreover, the extension of the recirculation agrees well. An important difference between the LSPIV and ADCP data is that the LSPIV method provides an almost instantaneous (30 s long) horizontal velocity distribution for the whole area, whereas the ADCP needs somewhat longer time (order of 10 minutes) to measure the transects which cover the study area. However, horizontal velocity distributions can also be produced from the ADCP data interpolating the velocities between the measured cross-sections. In overall, a clear advantage of the LSPIV method in this scale is the low money and time demand compared to other methods, and the indirect character of the surveys, i.e. no vessels are needed in the river, but the quality of the resulted flow information is comparable to acoustic methods and the data is limited to the free surface. Besides the cost-efficient and safer character of the method the detection of finer scale flow structures is also possible with the LSPIV technique as introduced in the followings.

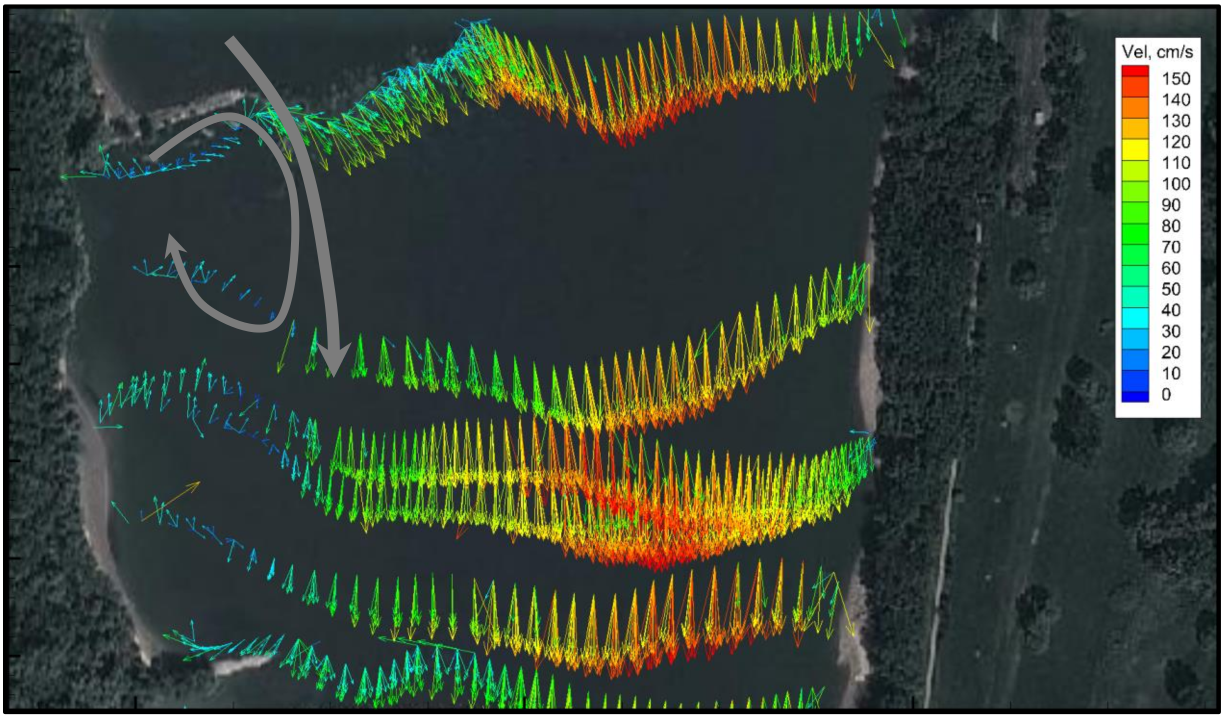


Figure 22. *Surface velocity vectors from moving boat ADCP measurements (Fleit, 2013)*

Attempts were made to detect the eddy structure, developing at the groyne tip. For this purpose, the video from the first measurement campaign was used, which was focused on a smaller area right at the groyne (see **Fig. 19**). Due to foam generated by the strong shear typical to this zone, the vortex shedding is visible by eye and is most probably detectable by the LSPIV method, too. There are several methods exist to identify eddies in flows (e.g. Nyers et al., 2008; Holmén, 2012). One of the simpler methods is to the calculation of the so called vorticity (around the vertical axis) according to the following formula:

$$\Omega = \frac{\partial \mathrm{v}}{\partial \mathrm{x}} - \frac{\partial u}{\partial y}$$

where: Ω is the Z vorticity

u and *v* are velocity vector components of *x* and *y* directions.

Another, widely used way of eddy detecting is the so called *Q* criterion:

$$Q = \frac{1}{2} \cdot (\Omega^2 + S^2)$$

where: Ω is the Z vorticity,

S is the strain rate:

$$S = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}$$

The eddy-scale LSPIV analysis requires different settings of the input parameters, since this method focuses on the correct instantaneous velocity fields as results, instead of the time-averaged velocity distribution. As typical to shear layers, the expected eddy structure at the groyne tip follows the Kelvin Helmholtz instability type vortex street (**Figure 23**).

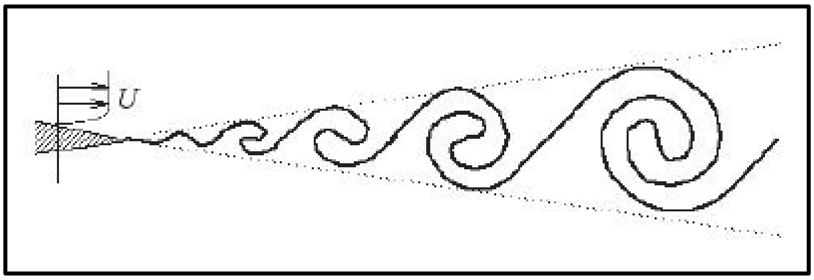


Figure 23. *Kelvin Helmholtz instability of a vortex street (Osamu, 2015)*

Due to the finer scale analysis higher frame rate and smaller interrogation area (IA) size are necessary to detect the small and fast moving eddies (**Figure 24**). After a thorough sensitivity analysis the following parameters were chosen:

- frame rate = 20 fps
- pixel size = 0.02 m
- IA size = 12 pixel
- correlation coefficient = 0.8
- length of the video = 20 s

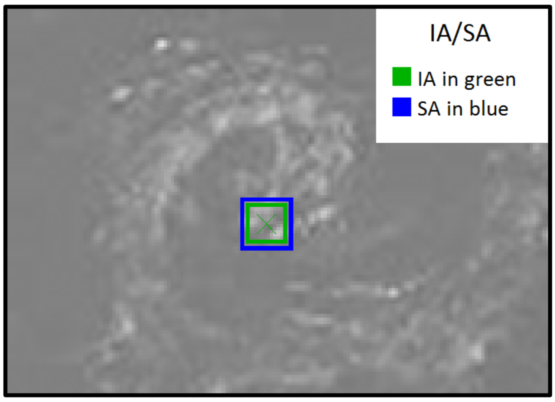


Figure 24. *IA/SA settings in eddy-scale LSPIV analysis*

Consequently, 400 images were processed, providing 399 instantaneous velocity fields. The instantaneous velocity fields were found to be too noisy (note the 20 fps means a time step of 0.05 s) and the eddies could not be well observed. To overcome this issue, the instantaneous velocity fields were smoothed with a moving averaging method, applying a window size of 3 seconds. A preliminary analysis was performed to determine the moving average window size. The Tecplot 360 software was used to calculate the horizontal distributions of the time-dependent vorticity and Q parameters based on the smoothed flow velocity vectors. The results of an 8 second long video are showed on **Figure 25 and 26** for the two parameters, respectively. Indicating the flow velocity vectors together with the patches of the two parameters, the developing eddy structure can be very well seen, which means that indeed the vortex structure can be captured using the LSPIV method. The calculated field allow us to e.g. estimate the typical eddy size resulted by the groyne. In this case the typical size of the eddy (see **Figure 25 or 26**) is about 1 m.

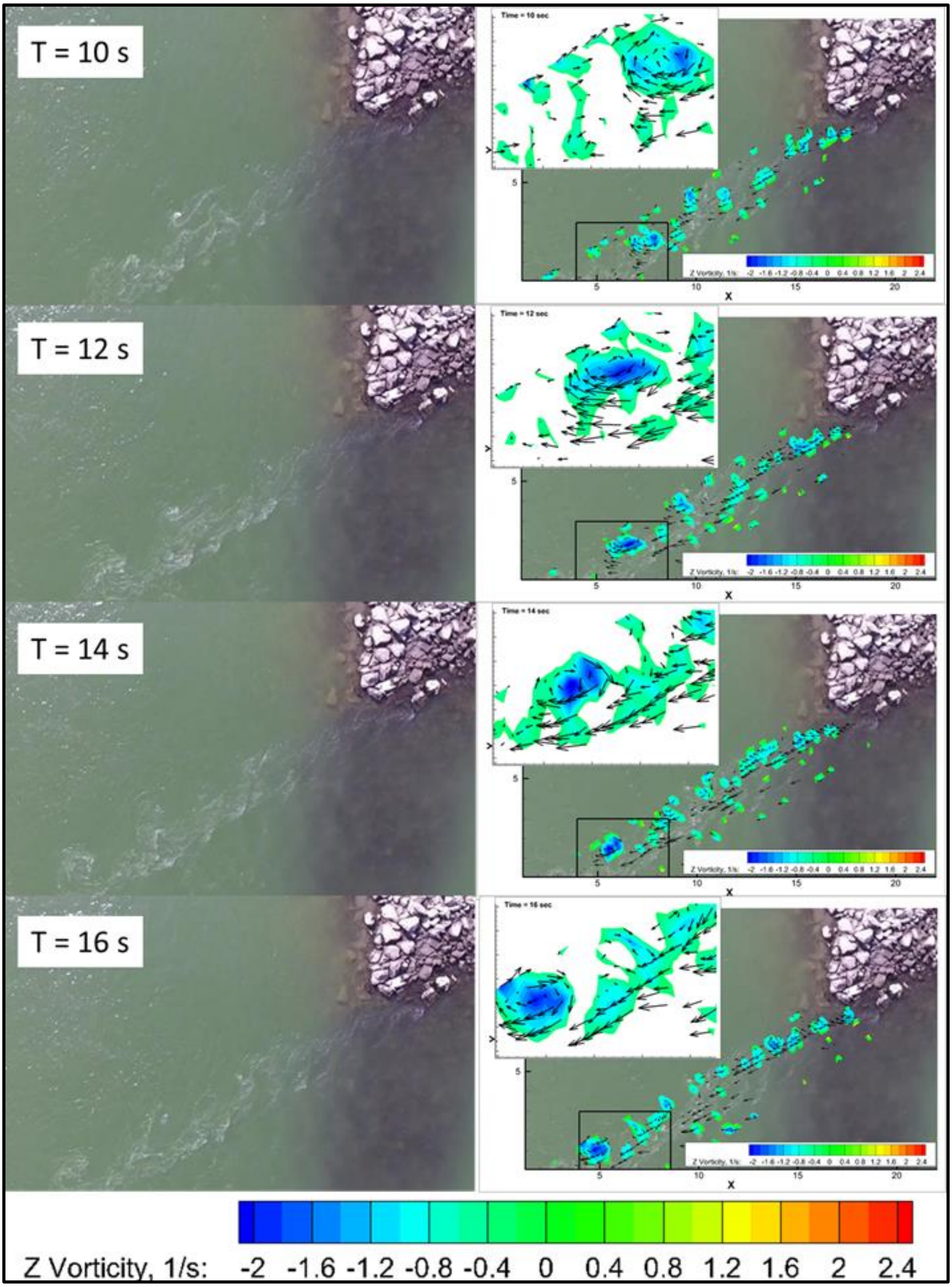


Figure 25. *Z Vorticity distribution near the groyne from LSPIV analysis*

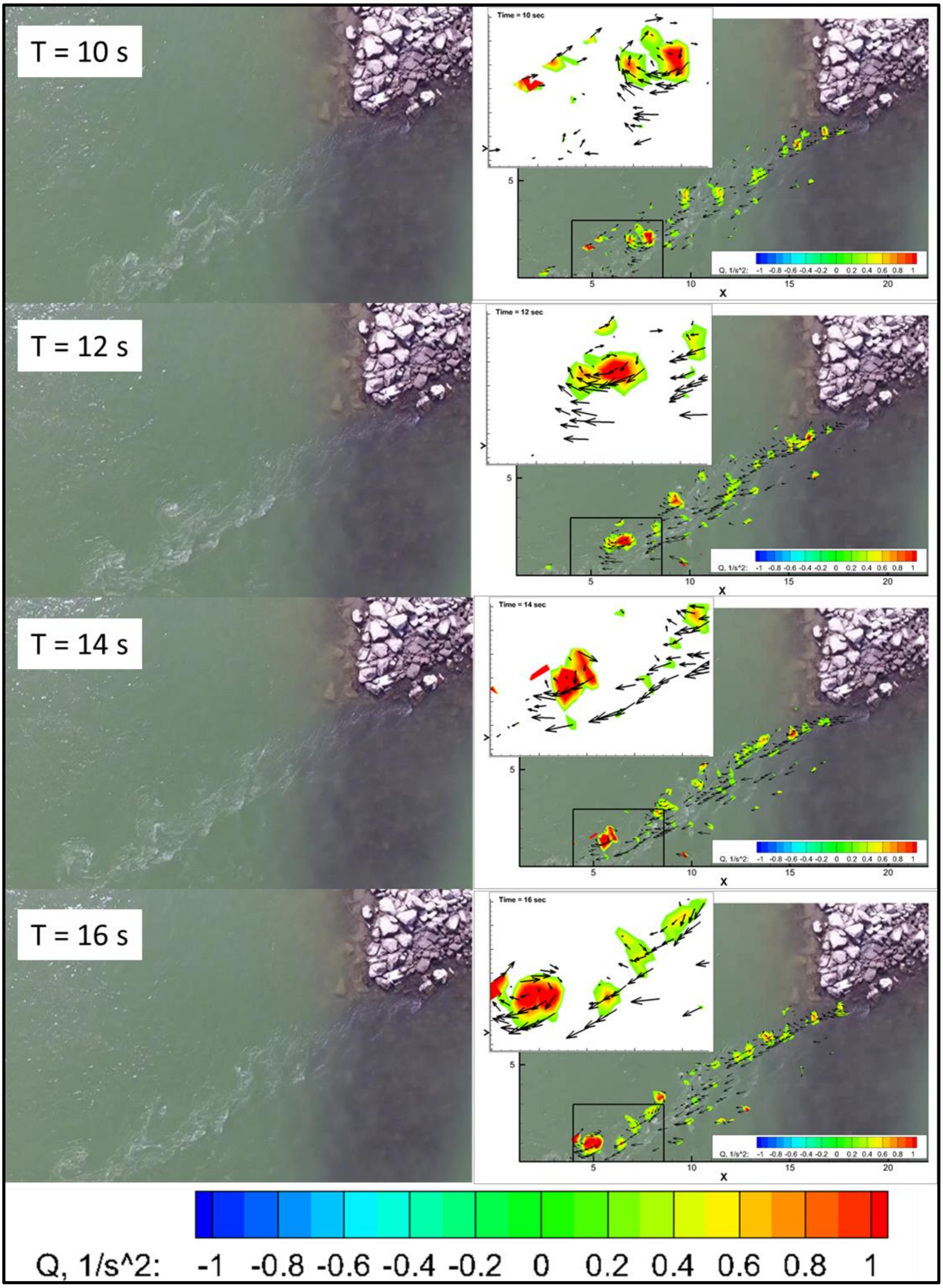


Figure 26. *Q distribution near the groyne from LSPIV analysis*

Besides the flow field based eddy detection methods an alternative way to estimate eddy size is to analyze the velocity time series of a point. In this case, the typical eddy size representative for the chosen point can be evaluated. The method used by e.g. Sokoray-Varga et al. (2007) takes the autocorrelation function of the velocity time series. The integral of the autocorrelation function, $\rho(\tau)$, is the Eulerian integral time scale (usually sufficient to the integral as far as the first zero point):

$$T_{EI} = \int_0^\infty \rho(\tau) d\tau$$

L_{EI} is the integral length scale by assuming the Taylor hypothesis:

$$L_{EI} = U \cdot T_{EI}$$

Eventually, this can be considered as an order of magnitude estimation of the energy containing dominant eddy size.

An attempt was made to estimate a typical eddy size at one point in the velocity field using this method (**Figure 27**).

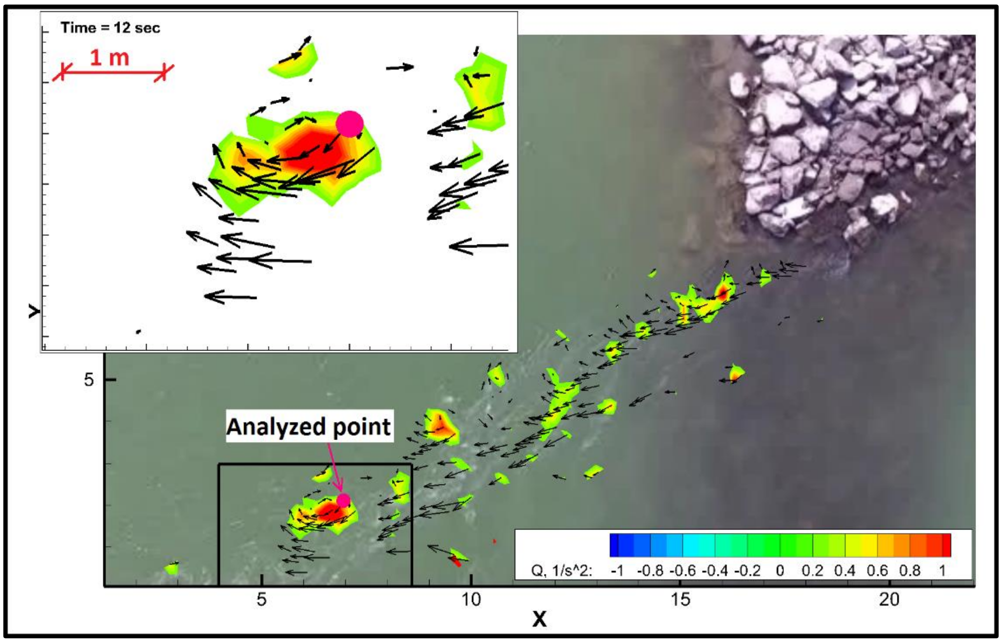


***Figure 27**. Analyzed point for the eddy size estimation*

First, the velocity time series at the chosen analyzed point were extracted of the instantaneous velocity fields which is shown on **Figure 28.**

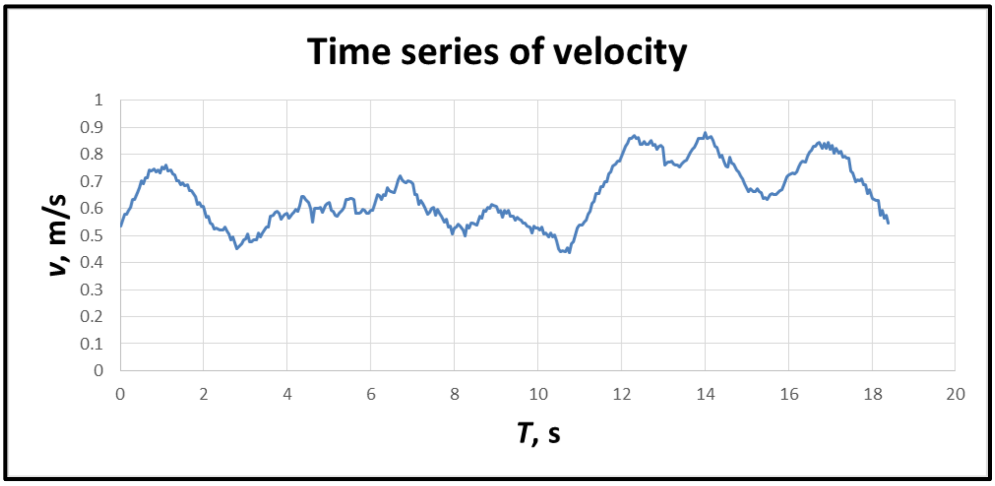


Figure 28. *Time series of velocity at the analyzed point*

Then the autocorrelation function of the velocity series was calculated (**Figure 29**).

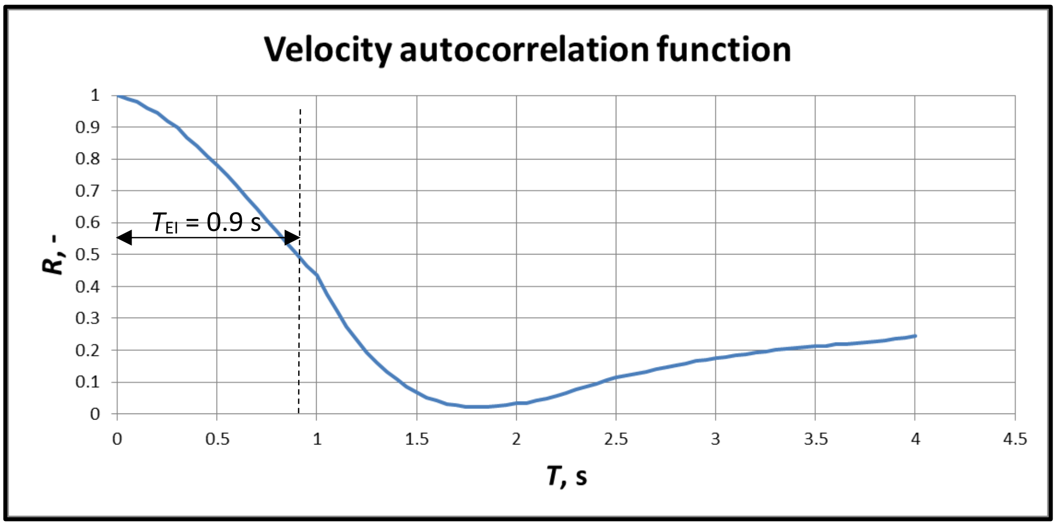


Figure 29. *Velocity autocorrelation function at the analyzed point*

The function was integrated until the first zero point (which in this case was estimated to be at 1.75 s). The resulted time scale, T_{EI}, was 0.9 s and considering a mean flow velocity of 1 m/s the calculated eddy size (L_{EI}) is 0.90 m, which agrees well with the estimation from the vorticity and the *Q* criterion. The results show that the LSPIV method is capable to capture the dynamic nature of the vortex shedding, moreover, quantification of the eddy sizes both in time and space is feasible. This sort of velocity field analysis is not feasible with any other technique in real (not laboratory) environment and shows a great potential in UAV based flow measurements. As to the authors knowledge no such real scale flow analysis was performed in the past.

3.2 Space-time image velocimetry (STIV)

3.2.1 Methodology and relevant literature

A new technique, space-time image velocimetry (STIV) may be an alternative image analysis method for measuring streamwise velocity distributions efficiently. The STIV method (Fujita et al., 2006) calculates from the time-change of brightness variation in a searching line set parallel to the main flow direction (**Figure 30**). The significant requirement of STIV is that there should appear a variation of brightness or color on the water surface moving with the surface flow. This variation is mainly caused by surface ripples generated by the confliction of boil vortices against the water surface. From a visual observation at the site, generation of boil vortices and the accompanied convection of the surface pattern can be easily detected. It was confirmed that the convection speed of the surface pattern agrees well with the surface floating tracers. The space-time expression of the brightness evolution in the line segment (searching line). The searching lines are shown in **Figure 31**. The brightness variation on the pixels of the searching lines changes by the time and the velocity is calculated from the slope of the outlined direction (**Figure 32**).

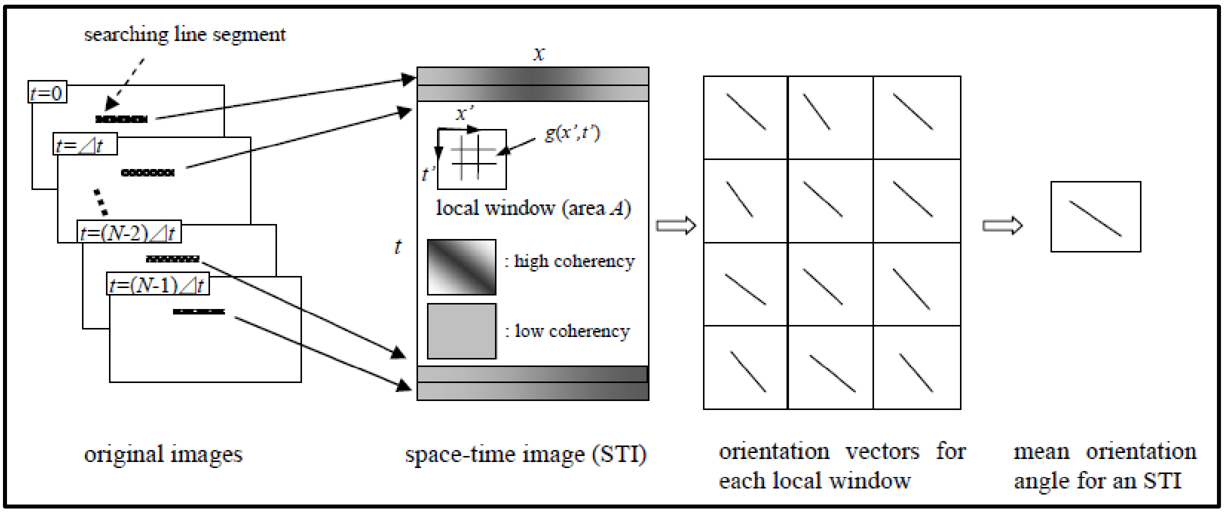


Figure 30. *STIV method*

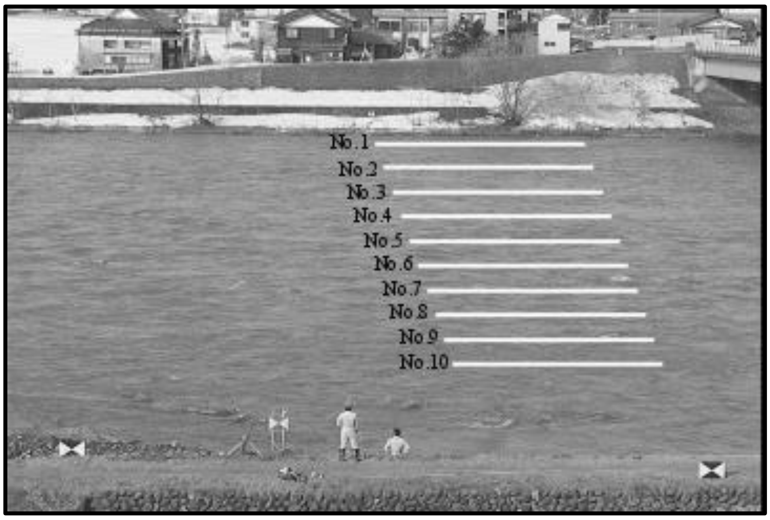


Figure 31. *Searching lines*

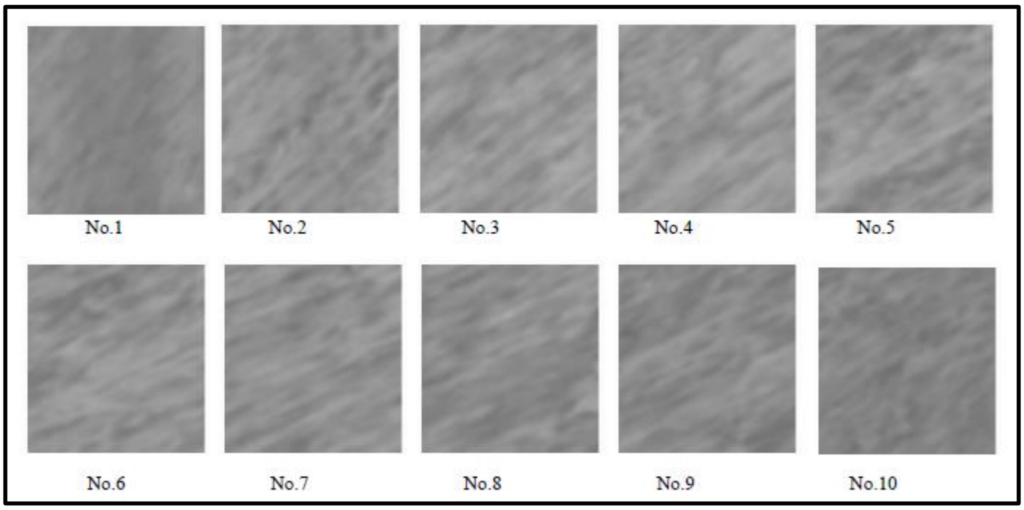


Figure 32. *Searching lines*

The UAV-based space-time image velocimetry (STIV) has the same problem as the LSPIV with the image processing (Fujita et al. 2015). The background displacement due to navigation or vibration of UAV has to be corrected accurately and efficiently since only 10 seconds long videos have been used. In order to establish this function, they combined several techniques. First, displacement, rotation and size change between the consecutive images are detected by using a RIPOC (rotation invariant phase only correlation) algorithm. Then, an efficient feature detection algorithm SIFT (scale invariant feature transform) is used to find feature points in the respective image. With the information of the coordinates of detected feature points, subsequent images are projected on the first image. Also, the aerial STIV results were compared to boat-mounted ADCP measurements. The measured data of both methods can be used to evaluate two dimensional numerical simulations. The same researchers show us a new image stabilizing method that utilizes novel intelligent image analysis techniques was developed for video images captured from aerial vehicles navigating along a river course in flood flow condition (Fujita et al., 2016). The developed method was applied to several new and old videos taken from a manned helicopter or an UAV. It was observed that the proposed method can produce hundreds of stabilized images quite efficiently, from which surface velocity distributions were obtained with reasonable accuracy. They compared the aerial LSPIV and aerial STIV results on the Yodo River (**Figure 33**).

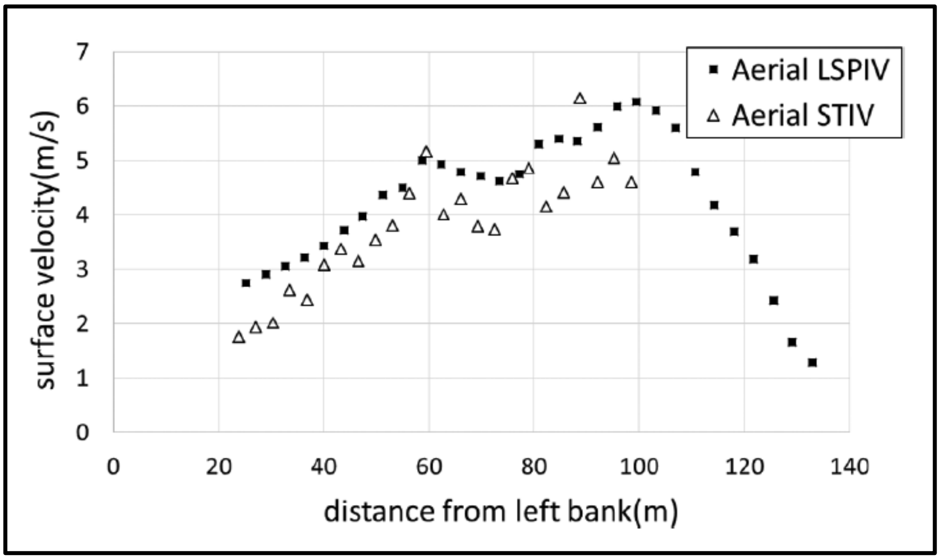


Figure 33. *Comparison of stream wise velocity distributions. By two methods at a cross section upstream from a bridge. (Fujita et al., 2016)*

3.2.2 Measurements and results

At this point of the study, the goal of the measurement was to test space-time image velocimetry (STIV) using images taken from an UAV. For the image processing the KU-STIV software from the Kobe University in Japan (http://www.kobe-u.ac.jp/en/NEWS/research/2016_04_22_01.html) was used. Also, a comparison with the LSPIV method was performed to assess advantages and disadvantages of the two methods. The measurement campaign was performed near Trondheim, Norway at the Lundesokna River on the 30th August 2016. The measurements have been carried out within the framework of a project called HydroCourse (http://www.hydrocourse.bme.hu). A DJI Phantom 4 Standard UAV was used for the video recordings, which has pretty much the same features as the earlier introduced Phantom 3 Standard UAV. The images were taken from 60 m above the ground. The raw image from the UAV and the analyzed cross-section is shown in **Figure 34**. There are small tracers on the water surface moving with the flow as well, which is essential to the LSPIV and also helpful to the STIV method.

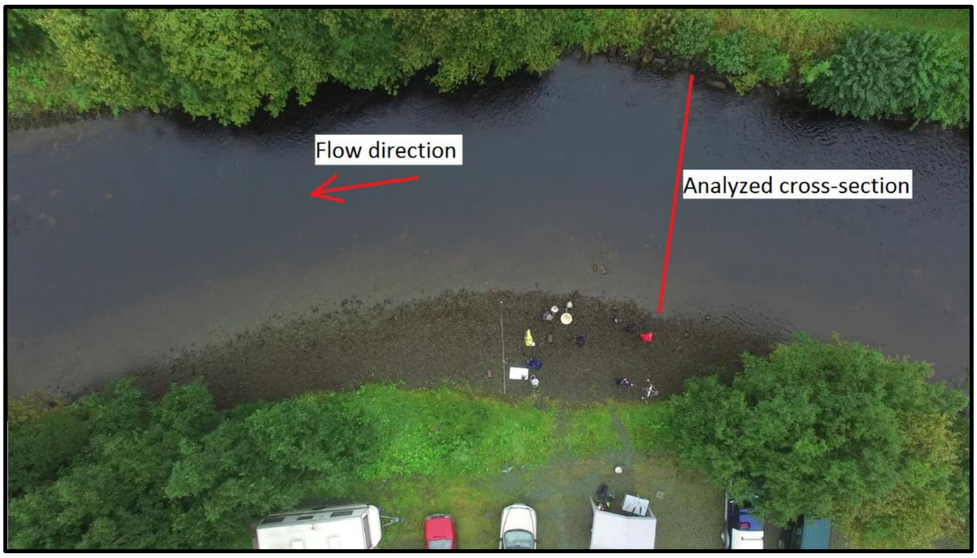


Figure 34. *Analyzed cross-section on the Lundesokna River from the UAV*

The KU-STIV software has just recently been started to use in Japan, where the tool was developed and has not yet been applied anywhere else. There is no well-written manual for the software which resulted in some difficulties, but after a thorough testing the image processing could be managed. A screenshot of the KU-STIV software is showed in **Figure 35**.

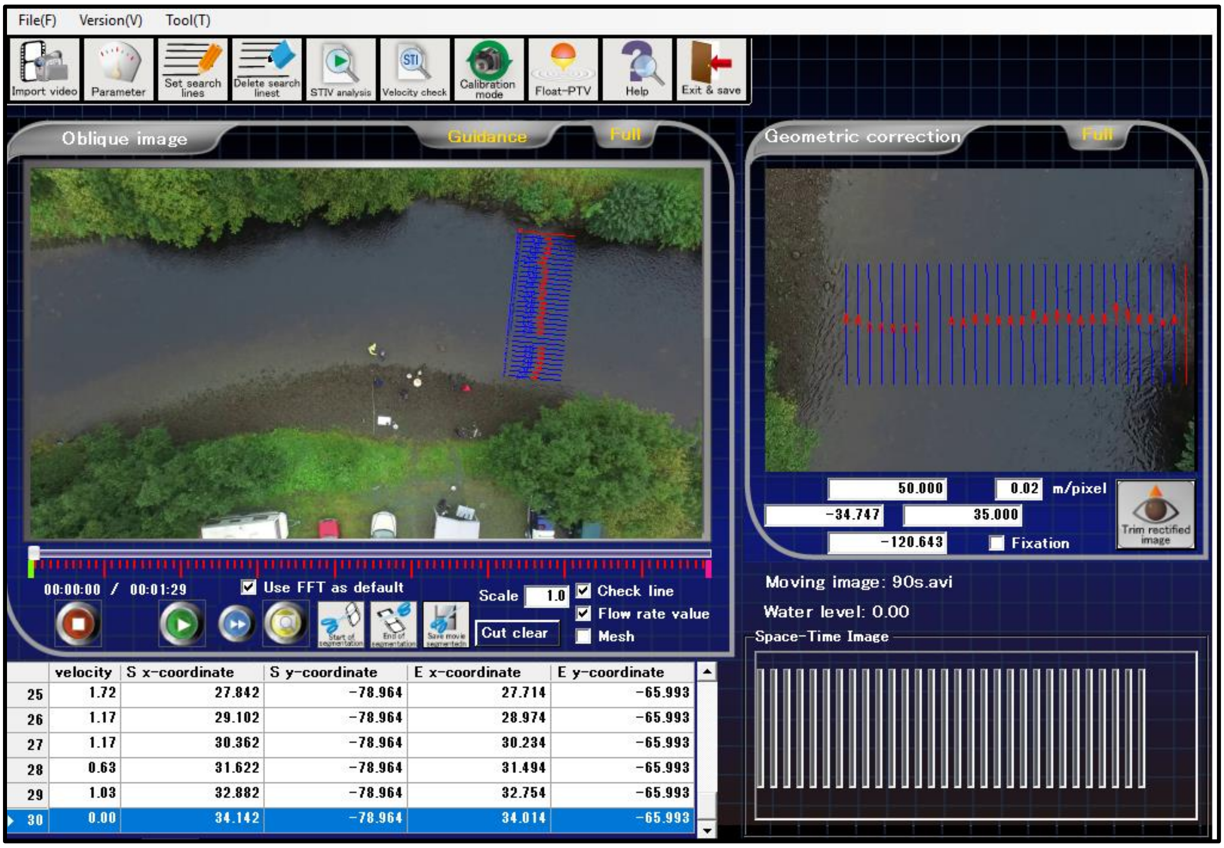


Figure 35*. The KU-STIV software*

The sensitivity analysis showed that the length of the analyzed video strongly influences the resulted velocity distribution. Also, the calibration parameters are important, such as the camera position and focal length, and obviously the reference points as well. The searching lines may not work when fix objects in the image interrupt, false values can be calculated. The length of the searching lines is also optional, but the velocity distribution may change too much at different cross-sections, and it will result in less accurate velocities.

After the preliminary tests the chosen video length was 90 s. The analyzed cross-section of the Lundesokne River was 30 m wide, and 30 searching lines were placed to calculate the velocity distribution. Meanwhile, LSPIV analysis was done using the very same video and parameters (e.g. image resolution), except the searching lines, where grid points were defined instead, 30 grid points at a cross-section. The raw results of the two methods are shown in **Figure 36**. The resulted surface velocity distribution is showed in **Figure 37**.

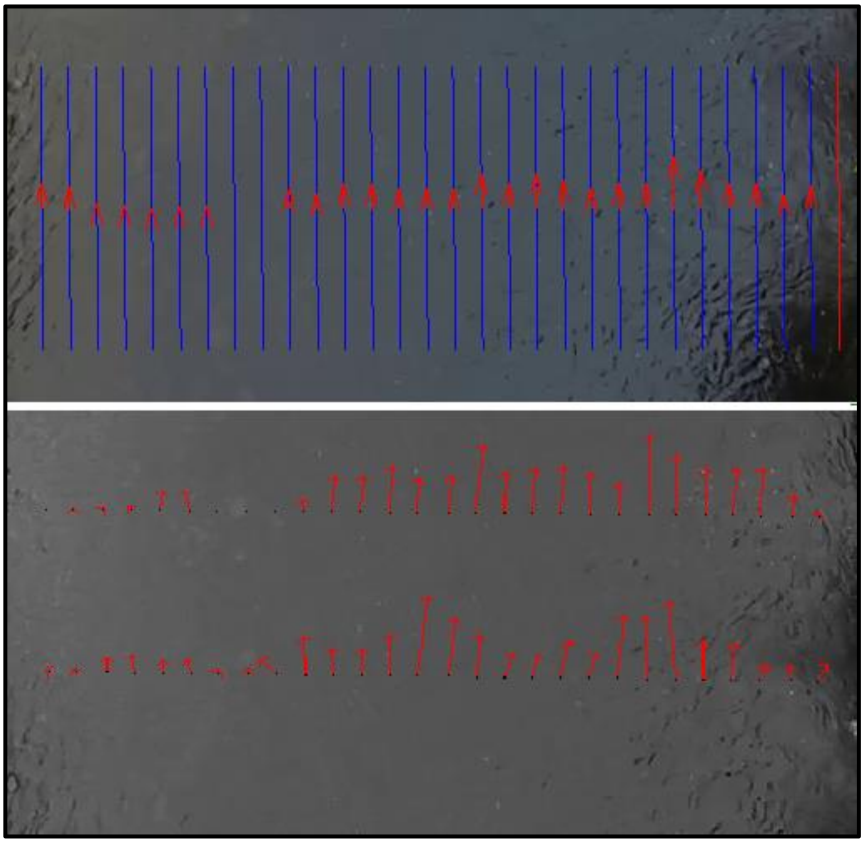


Figure 36. Raw STIV and LSPIV results

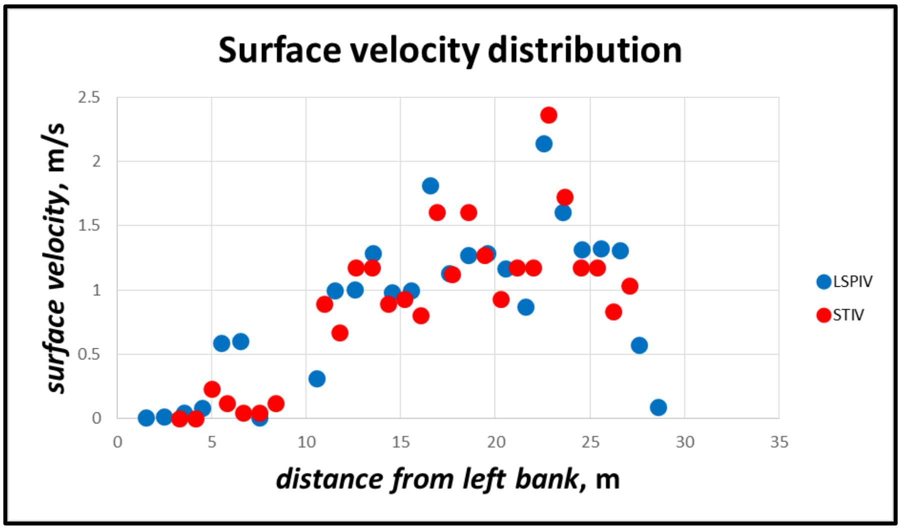


Figure 37. Velocity distributions with LSPIV and STIV methods

The average velocity calculated with the STIV is 0.897 m/s and 0.874 m/s with LSPIV, respectively, showing a difference of less than 2.5 %. Based on this agreement it can be concluded that the UAV-based STIV method have a great potential in calculating streamwise velocities of rivers. However, due to the fact that STIV determines flow velocity along parallel lines it cannot be used for more complex flow conditions, such as the ones analyzed in the previous points. The main advantage of STIV is that the actual velocity calculation part is faster than the LSPIV method and so the real time discharge measurement can be more robust.

Moreover, according to the tests of the developer (Fujita, 2016) a further advantage of the STIV method was it is accuracy against LSPIV, the sunlight refraction, for instance, cannot disturb the method. Further testing is necessary on the STIV measurements, such as ADCP data comparison.

4 Summary and conclusions

River flow and topography measurements have been done using cost-effective and user-friendly UAVs for data collection and open source software were utilized for the data processing in this study. Detailed literature research was performed of the relevant topic as well. As to the topographic surveys three different real objects were 3D modeled using the SFM method. The field surveys take 10-20 minutes all together, whereas the image processing takes a couple of hours for an area size of a few 100 m^2. The reconstructed 3D structures were added to an existing DTM of the study area to illustrate one of the typical applications of such a measurement. This means at the same time that much larger areas could be assessed, even several 1000 m^2, and the preparation of DTMs based on the SFM is not only faster, but much more cost-efficient than laser scanning. Besides the topographic surveys flow analysis based on UAV surveys was also carried out. The LSPIV analysis was two-fold, both showing very promising results. First, the time-averaged surface velocity field was calculated in the vicinity of a groyne, where the local flow contraction could be well shown with high velocities as well as the nearly zero velocities in the recirculation zone, in fact following the expected behavior in such regions. The LSPIV method worked robust even with large oblique angle, which usually makes the orthorectification less accurate, but the velocity distribution was realistic compared to recently collected ADCP data at the same area (Fleit, 2013). Using carefully chosen parameter settings after a thorough sensitivity analysis, the LSPIV process was found to be quite fast as well, for instance, a 30-second-long video of a large section of a river could be analyzed in a few minutes. Based on the observation in the field and also shown by the UAV videos, eddy development could be well seen at the groyne tip, and so an attempt was made to detect and quantify this dynamic flow structure. A more detailed LSPIV analysis was necessary to reveal the vortex shedding, i.e. focusing on the shear layer and using much higher resolution. For the quantification, the vorticity and the Q parameters were calculated based on the instantaneous flow velocity fields. Based on the fields of these two parameters the typical eddy size was estimated, moreover, it was compared to another estimation method which is based on the velocity autocorrelation function, and the estimations matched well. It could be concluded that the LSPIV method works stable and is reliable both in larger or smaller scale too. In the last part of this study, a novel image based velocimetry technique, the STIV was tested using UAV-based videos. Measured cross-sectional flow velocities in a smaller river were compared with LSPIV, and a good agreement was shown. In overall, the very first applications of drone based topographic and flow measurements showed very promising results. Although SFM applications can already be found in the literature, this sort of combined river engineering application is novel, moreover, the introduced flow assessment results are believed to be pioneer.

5 Potential future applications

As introduced in this study, UAVs can collect a large amount of data faster than ever. The UAV-based measurements have huge potential for future research. The applications of the introduced techniques in this study need to be further analyzed, furthermore, new opportunities with UAVs have to be continuously considered. For instance, thermal imaging cameras could be mounted on the UAV, providing a suitable tool for analyzing the mixing processes of cooling water at power plants. UAVs could also be used for assessing sediment resuspension caused by the breaking of ship induced waves (Fleit, 2015) and littoral erosion, since the phenomenon is reasonably visible from the UAV videos (**Figure 38**).

Figure 38*. Sediment resuspension patterns seen from the UAV*

Another potential application field can be the detection of morphological evolution of rivers in river bends using the UAV-based SFM method. As a hot topic in these days, especially close to urban areas, the tracking of debris flow could be performed with UAV measurements. In this case the erosion zone at the source, the transport zone and the deposition zones could be mapped from the air. Such an information would be essential for numerical modeling applications. UAV based imaging could well contribute to flood inundation studies with field data if dyke failure happens. The SFM method could reconstruct the temporal behavior of dyke failures, surveying the change of the dyke geometry, moreover, the hydrodynamics in the surrounding of the breach and the propagation of the flood on the floodplain can be tracked. Besides all the previously mentioned points, a very likely continuation of this study is to perform UAV-based Particle Tracking Velocimetry analysis in the Danube River, to reveal the eddy structures in the vicinity of different structures using a Lagrangian approach, moreover, the chaotic nature could be quantitatively assess with this method.

6 Bibliography

[1] Fujita, I.; Muste, M; Kruger, A. Large-scale particle image velocimetry for flow analysis in hydraulic applications, *Journal of Hydraulic Research*, 36(3), 397–414. 1998

[2] Muste, M., Fujita, I., Hauet, A.: Large-scale particle image velocimetry for measurements in riverine environments, *Water Resources Research*. Vol. 44, 2008

[3] Tauro, F., Pegano, C., Phamduy, P., Grimaldi, S., Porfiri, M.: Large-Scale Particle Image Velocimetry from an Unmanned Aerial Vehicle, *IEEE/ASME Transactions on Mechatronics.* 2015a

[4] Tauro, F., Petroselli, A., Arcangaletti, E.: Assessment of Drone-based Surface Flow Observations, *Hydrological Processes*. 2015b

[5] Patalano, A., García, C.M., Brevis, W., Bleninger, T., Guillen, N., Moreno, L., Rodriguez, A.: Development of UAV-based river surface velocity measurement by STIV based on high-accurate image stabilization techniques, *IAHR Papers*. 2015

[6] Patalano, A., García, C. M.: RIVeR – Towards affordable, practical and user-friendly toolbox for Large Scale PIV and PTV techniques, River Flow. 2016

[7] Fujita, I., Watanabe, H., Tsubaki, R.: Development of a non-intrusive and efficient flow monitoring technique: the space-time image velocimetry (STIV), *International Journal of River Basin Management*. 2006

[8] Fujita, I., Hino, T.: Unseeded and Seeded PIV Measurements of River Flows Videotaped from a Helicopter, *Journal of Visualisation*, Vol. 6., No. 3. 2003

[9] Fujita, I., Kunita, Y.: Application of aerial LSPIV to the 2002 flood of the Yodo River using a helicopter mounted high density video camera, *Journal of Hydro-environment Research*, Vol. 5., 323-331. 2011

[10] Fujita, I., Notoya, Shimono: Recent Advances in Eulerian and Lagrangian Large-Scale Particle Image Velocimetry, *IAHR Papers*. 2015

[11] Fujita, I., Notoya, Y., Tateguchi, S.: Development of efficient image stabilization algorithm for airborne video images and its application to river flow measurements*, River Flow*. 2016

[12] Detert, M., Weitbrecht, V.: Helicopter-based surface PIV experiments at Thur River, River Flow. 2014

[13] Detert, M., Weitbrecht,V.: A low-cost airborne velocimetry system: proof of concept. *Journal of Hydraulic Research*, Vol. 53., 532-539. 2015

[14] Detert, M., Huber, F., Weitbrecht, V.: Unmanned aerial vehicle-based surface PIV experiments at Surb Creek, *River Flow*. 2016

[15] Blois, G., Best, J.L., Christensen, K.T., Cichella, V., Donahue, A., Hovakimyan, N., Kennedy, A., Pakrasi, I.: Assessing the the use of UAV to quantify flow processes in rivers, *River Flow*. 2016

[16] Le Coz, J., Thollet, F., Hauet, A., Pénard, L., Le Boursicaud, R.: Gauging extreme floods on Youtube: application of LSPIV to home movies for the post-event determination of stream discharges, *Hydrological Processes*. 2015

[17] Jodeau, M; Hauet, A; Le Coz, J.: Fudaa-LSPIV 1.3.2 User guide. EDF R&D, EDF DTG, Irstea. 2013

[18] Lükő, G.: Analysis of video-based discharge measurement method for streams, BME-VVT, TDK dolgozat. 2015

[19] Kerék, G.: Videó alapú vízhozammérések alkalmazhatósága kisvízfolyásokon, BME-VVT, Szakdolgozat. 2015

[20] Lükő, G., Baranya, S.: Videó alapú vízhozam-mérés tesztelése kisvízfolyásokra, *Magyar Építőipar*, 2016

[21] Fleit, G.: Élőhely szempontú folyószabályozás megalapozása korzserű hidromorfológiai adatelemzéssel, BME-VVT, TDK dolgozat. 2013

[22] Fleit, G.: Hajók keltette hullámzás hatásának terepi feltárása a litorális zónában, BME-VVT, TDK dolgozat. 2014a

[23] Fleit, G.: Élőhely szempontú folyószabályozás támogatása korszerű terepi mérésekkel és számítógépes modellezéssel, BME-VVT, TDK dolgozat, 2014b

[24] Fleit, G.: Comprehensive analysis of ship induced waves by means of field and computational methods, BME-VVT, TDK dolgozat. 2015

[25] Nyers, T., Tóth, P., Lohász, M. M.: Tracking of vortices in computational fluid dynamics, Budapest University of Technology and Economics. 2008

[26] Holmén, V.: Methods for vortex identification, Lund University, Master's Thesis. 2012

[27] Sokoray-Varga, B., Baranya, S., Józsa, J.: Turbulence analysis of slot fish pass by in situ measurements and CFD modeling, *River Flow.* 2006

[28] Osamu, S.: Vortex formation behind an object. 2011.

[29] Niethammer, U., Rothmund, S., Schwaderer, U., Zeman, J., Joswig, M.: Open source image-processing tools for low cost UAV-based landslide investigations, *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* Vol. XXXVIII-1/C22. 2011

[30] Turner, D., Lucieer, A., Watson, C.: An Automated Technique for Generating Georectified Mosaics from Ultra-High Resolution Unmanned Aerial Vehicle (UAV) Imagera, Based on Structure from Motion (SfM) Point Clouds, *Remote Sensing*, Vol. 4., 1392-1410. 2012

[31] Crandall, D., Owens, A., Snavely, N., Duttenlocher, D.: Discrete-Continuous Optimization for Large-Scale Stucture from Motion, IEEE Transactions on Pattern Analysis and Machine Intelligence,

[32] Ullman, S.: Interpretation of Structure from Motion, *The Royal Society*. 1979

[33] James, M. R., Robson, S.: Straightforward reconstruction of 3D surfaces and topography with a camera: Accuracy and geoscience application, *Journal of Geophysical Research*, Vol. 117. 2012

[34] Rootwelt, T.: Sructure from motion, turtable based reconstruction, Norwegian University of Science and Technology. 2014

7 Appendix

7.1 SFM Image processing protocol

The steps of the image processing method from the available MOV file recorded from the UAV, to the PLY file (georeferenced point cloud):

I. ffmpeg (https://ffmpeg.org/ffmpeg.html) from the Command Line
   1. Convert from MOV to AVI
   2. Cut the necessary length of the video

```
C:\Windows\System32\cmd.exe
Microsoft Windows [Version 10.0.14393]
(c) 2016 Microsoft Corporation. Minden jog fenntartva.

C:\A_TDK_2016\trondheim_STIV-LSPIV>ffmpeg -i input.avi -acodec copy -vcodec
copy -ss 00:02:00 -t 00:00:30 output.avi_
```

   This will make a new 30 s long video, starting from 2:00.

II. VirtualDub (http://www.virtualdub.org/virtualdub_docs.html)
   1. File/Open (AVI)
   2. Video/Frame rate (set necessary frame rate, usually max 30fps)
   3. File/Export/Image sequence (JPG)

III. VisualSFM (http://ccwu.me/vsfm/doc.html)

The software needs to be started from a folder which contains the list of files shown below. If SiftGPU was not in the original package, it is available here:

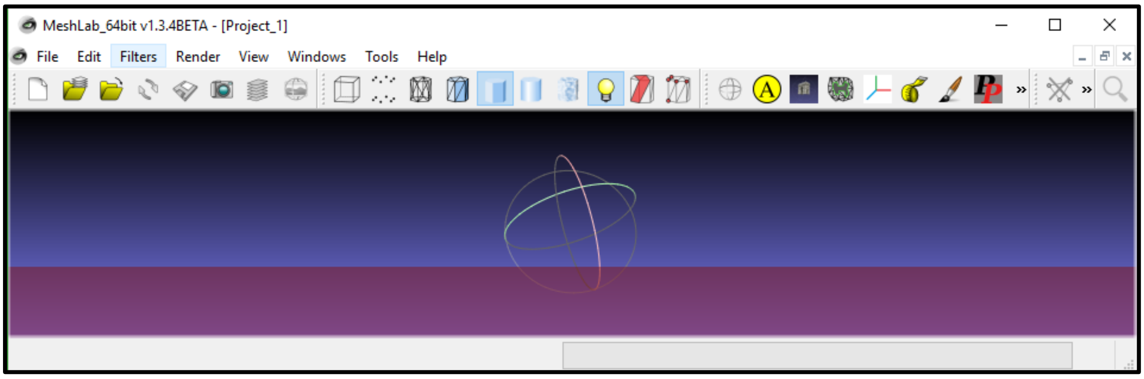
http://wwwx.cs.unc.edu/~ccwu/cgi-bin/siftgpu.cgi

log	10/25/2016 4:16 PM	Fájlmappa	
SiftGPU-V400	10/1/2016 1:40 PM	Fájlmappa	
cmvs	9/18/2016 2:35 PM	Alkalmazás	1,135 KB
genOption	3/23/2015 5:29 AM	Alkalmazás	33 KB
glew64.dll	6/2/2010 7:19 PM	Alkalmazáskiterjes...	273 KB
nv	8/10/2016 2:14 PM	Konfigurációs beá...	7 KB
pba_x64.dll	12/13/2012 8:16 PM	Alkalmazáskiterjes...	253 KB
pmvs2	3/23/2015 5:29 AM	Alkalmazás	1,639 KB
README	3/11/2015 4:56 AM	Szöveges dokume...	3 KB
SiftGPU64.dll	10/11/2012 10:46 ...	Alkalmazáskiterjes...	424 KB
VisualSFM	8/10/2016 2:14 PM	Alkalmazás	1,353 KB

The VisualSFM software interface can be seen below, as well as the next steps. The 2D images and the 3D structure will be seen in the main window on the left, and messages will be in the log window on the right.

1. File/Open+ Multi Images (JPG)
2. SfM/Pairwise Matching/Compute Missing Matches
3. SfM/Reconstruct Sparse
4. SfM/Reconstruct Dense (output: NVM and PLY file)

IV. Meshlab (http://www.cyi.ac.cy/system/files/MeshLab%20Documentation1.pdf)
The Mashlab interface is shown below as well as the next steps.



1. File/Import mesh (PLY)
2. Edit/Select Vertexes (select unnecessary points to delete)
3. Filters/Selection/Delete Selected Vertexes
4. Render/Show Axis (will see the mesh in a random axis)
5. Filters/Normals, Curvatures and Orientations/Transform: Move, Translate, Center (set the direction of the zero axis into the center of the mesh)
6. Filters/Normals, Curvatures and Orientations/Transform: Rotate (rotate the Y, Y, Z axis according to reality)
7. Edit/Reference Scene
8. “Add New Point”
9. “Pick current point on MOVING” (then click on the reference point on the mesh)
10. Fill the X (ref), Y (ref), Z (ref) with the real coordinates of the points (only takes 6 digit numbers)
11. Repeat the last 3 steps to each reference point
12. Tick both “Allow UNIFORM Scaling” and “Apply to all VISIBLE layers”
13. “Calculate Rototranslation” (error of each point is shown)
14. “Apply”
15. Filters/Normals, Curvatures and Orientations/Freeze Current Matrix
16. Tick “Apply to all visible layers”

17. “Apply”
18. File/Export Mesh
19. Untick “Binary encoding” and “Normal” (Vert)

Now the georeferenced PLY file is openable via Notepad and the first 3 columns of the text contain the X, Y, Z coordinates of the point cloud of the object.