The Application of Unmanned Aerial Vehicles and Photogrammetry to Hydraulic Surveying

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1.0 Introduction

1.1 Hydraulic surveying involves the mapping of rivers, their catchments and floodplains, as well as measurements of their hydraulic properties; mainly volumetric flow rate and hydraulic cross section. Such surveys are necessary to properly manage our rivers, informing the planning of the development of surrounding land and watercourse management strategies. Such information is vital for government agencies, particularly the environment agency but also local councils. Private developers, insurers and a host of other stakeholders also require accurate information and are mainly concerned with flood risk. However, accuracy of measurement alone is not enough, as rivers are constantly evolving with erosion and deposition altering their properties. In fact the environment agency is in the constant process of updating their hydraulic models with each major river in the UK reassessed every 5 years. It is therefore important to have methods which are accurate, fast and, with the ever present pressure on public spending, cheap. [2]

At present most hydraulic surveying is carried out using a combination of traditional surveying techniques and LIDAR surveys. Traditional surveying is slow and labour intensive requiring skilled surveyors using total stations and targets to build up a network of known points through triangulation, to effectively map a large area can take a considerable amount of time and therefore also money. LIDAR surveys use laser technology with transmitters and receivers mounted in aeroplanes a fairly detailed (roughly 2m resolution) elevation map of an area can be quickly generated but at quite considerable cost. [4]

Flow measurements for rivers are usually made at controlled cross section locations with concrete channel sections and flow meters. These are very accurate and fairly inexpensive but many are needed to build up a detailed model of a river as flow characteristics between these known points must be interpolated. [5]

1.2 UAVs (unmanned aerial vehicles) offer an opportunity to provide much of the information needed for hydraulic surveying at a fraction of the time and cost of current methods. UAVs capable of carrying the required equipment (a high quality camera) are available for a relatively low cost and can be flown with relatively little training (in comparison to that needed for the surveying alternatives).

1.3 Photogrammetry is the technology that enables camera equipped UAVs to be used for surveying. One photogrammetry technique, Structure From Motion (SFM) is the use of multiple photos of the same area/object from different positions to build up a 3D model. For surveying purposes this can be used to build a surface model of flood plains around rivers. A cloud of points is produced with each point corresponding to a location on the ground recording its position and ground elevation. Another photogrammetry technique, Particle Image Velocimetry (PIV) uses multiple images of a moving surface taken from the same position at different times. These can be used to produce a velocity field. In hydraulic surveying this could be used to find surface velocities over a river's cross-section which can be used to infer the flow rate.

The key part of both techniques is point identification. Each photo is processed by an algorithm that seeks out recognisable points. Groups of pixels with clear patterns (variations of colour or brightness) are identified and marked as points in the image. An example is the FAST (Features from Accelerated Segment Test) algorithm. This finds "corners" by checking the brightness of a ring of pixels. Where a segment of the ring differs in brightness from the rings centre a point is identified.

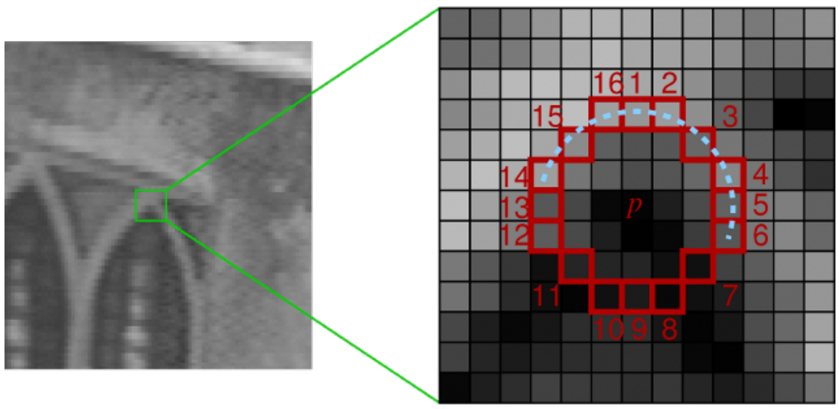


Fig. 1 FAST algorithm visualisation [1]

Varying the radius of the ring (and number of pixels that defines the “centre”) allows features of different sizes to be found within the image.

Once each image has been broken up into identifiable points, point matching between images can occur: points in different images are compared and where the pattern of pixels that makes up the points match, these points can be shown to be common between images.

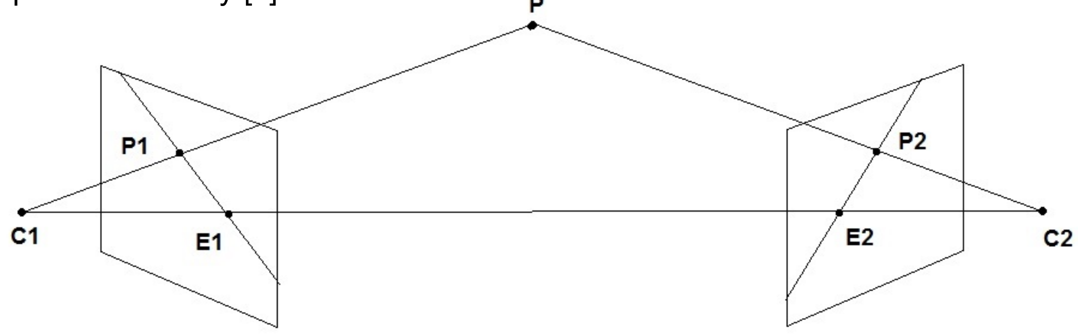
In velocimetry the field of view within the images is consistent with points within the field moving between images. The distance between matched points within subsequent images can be divided by the time between images being taken to determine the velocity at that point. Repeating this process for multiple points produces a velocity field.

$$\mathbf{v} = (\mathbf{x}_2 - \mathbf{x}_1) / t$$

A correction also needs to be made for perspective, which distorts distances within the photograph. Taking images from directly above the interest area and at a reasonable distance reduce this effect but it is also accounted for with distances simply scaled by position in the image.

In structure from motion images are taken from different locations so by taking vectors from multiple camera locations the matched point’s position can be determined from the epipolar geometry.

Fig. 2 Epipolar Geometry [1]



The basic matrix equation being solved between each pair of images is:

$$X^T F X' = 0$$

With matrix F encompassing the camera characteristics, positions and orientations in relation to point P and X and X' being the vectors to all the matched points from each photo location. F has 7 degrees of freedom, which means at least 7 common points are required between 2 photos, further points will lead to a least squares solution for F.

Matching between each pair of photos with common points produces a geometry with point and camera positions. In Pix4D these are then combined with the camera positions obtained from GPS and an optimum solution found through bundle adjustment. Effectively finding an average between so many points in each image, with many images and camera positions is a fairly intensive computing task, with run times on a standard PC of several hours. The result however, should be an accurate and detailed point cloud that would take far longer to obtain through traditional surveying and through much greater expense with LiDAR surveys.

It should be noted that it is relative position between points that is found accurately here, the only absolute positioning comes from the UAVs GPS data, which while adequate for relative positions can be several meters out in absolute position (and worse for altitude). Pix4D allows control points to be identified to fix the point cloud in an absolute position. A known point is manually picked out the point cloud and assigned its known position with the the whole point cloud shifted to fit.

The aim of this project will be to use these photogrammetry techniques in conjunction with a UAV to carry out hydraulic surveying and thereby access both the practicality and accuracy of this method and find the optimum way to carry it out.

2.0 Equipment and Software

In this project the DJI Phantom 4 Pro drone has been used as our UAV. The Phantom 4 is an affordable but highly usable piece of equipment. Retailing for around £1000 this UAV carries an HD camera and can be controlled via freely available software on

IOS or Android. It is also GPS enabled allowing the drone to have flights pre-programmed and crucially to record the position of photos taken, for use in photogrammetry. The battery allows around 30 minutes of flight time.

Photos from the drone were processed using Pix4D software. The trial version was sufficient to produce the point cloud with the £200+ per month version of the software allowing the user to create various maps and carry out other functions with the point cloud produced. However, in order to test the accuracy and usefulness of the UAV/Photogrammetry technique only the raw data and point cloud are required. Various pieces of software where used for our velocimetry experiment. Various freely available codecs and video editing software were used to get video footage into a useable format. Matlab and Matlab add ons River and PIV Lab, where used to carry out the velocimetry analysis. Matlab scripts written by my project partner (Luis North) were also used to compare the point clouds produced by pix 4D to ones produced from LIDAR surveys in our experiment area.

3.0 Locations

Four separate locations where used for this project. PIV testing was carried out by the weir at Jesus lock, the sluice gate at the Mill and on the rush. All three were chosen due to the higher velocity flows found in these areas which are easier to detect using PIV.

SFM testing was carried out on a section of the Coe Fen either side of a drainage channel. This location had the varying ground elevation around the channel we wanted to try measuring using the technique, whilst also allowing a test grid to be set up at a reasonable scale to allow multiple tests. The proximity to the engineering department and relatively low pedestrian traffic during the day were also helpful.

Fig. 3 Survey Locations

4.0 Method

4*.1 The Structure From Motion* Technique depends on the same point being identified across m multiple images, so that the position of the point (and that of the camera when taking the photographs) can be accurately determined using statistical techniques. It is therefore expected that a higher quality image will yield more accurate results because more precise points will be able to be picked out in each image. Whilst the camera on our drone is the same throughout the altitude the drone flies may be expected to impact the photo quality as pictures from further away will have an effectively lower resolution at ground level (each pixel will represent a greater area of ground).

One might also expect the accuracy of any measurements to be improved by maximising the overlap between images because greater overlap between images will yield more matched points between images, providing more information to obtain positions.

The aim of the following tests is to confirm the relationship between UAV flight altitude, overlap and positional accuracy and then determine whether the achieved accuracy is sufficient for hydrological surveys and which flight parameters yield the best balance of accuracy and flight time.

To test the structure from motion technique in conjunction with the UAV the following test was devised:

1. A grid of 5 points was set up on the Coe Fen and each points position determined using traditional surveying techniques
2. A total of 28 flights were flown above the grid varying the altitude whilst keeping the image overlap fixed and vice versa
3. the point cloud produced using Pix4D software from each flight was then analysed and the position of the five known points extracted
4. the vectors between the five points found using SFM were then compared to the known vectors obtained from the positions found using traditional surveying (the

vectors were compared rather than the absolute position because the absolute location of the point cloud is determined using GPS data from the Drone and is therefore liable to be as much as +/- 10m out horizontally and worse vertically, the relative position between the points within the point cloud is determined by the SFM technique)

5. comparing the error of the SFM found vectors compared to the true vector then gives an indication of the accuracy

Absolute accuracy can be obtained using the Pix4D program by fixing points within the cloud manually: points of known position can be manually identified in the cloud and the whole cloud is the translated to match. This facility was tested by fixing the cloud to varying numbers of our control points but this was not done in the main test of accuracy using only the relative positions to ensure only the SFM technique was being tested.

The 28 flights were carried out in michaelmas term and results processed before lent term. In lent further flights were flown to repeat settings where anomalous results were found and to carry out more flights around the overlap and altitude levels found to be most accurate.

Fig. 4 SFM Grid Approximate Layout

4*.2 The Particle Image Velocimetry* technique relies on identifying points in subsequent images to find their change in position which can then be divided by the time interval between images to give a velocity. Therefore the two required key features of the images is that they are stationary, i.e. subsequent photographs are taken from the same position and captures the area, so that displacements of matched points are solely down to movement of the point and not of the image. Secondly the point finding algorithm must be able to identify clear points in multiple images. This can be affected by numerous factors: the availability of recognisable features in the flow being studied, which can be a challenge in water flows as the surface is very uniform; also the time between images needs to be long enough to show a recognisable displacement of the points (long enough for a point to move a distance of at least the same magnitude of the size of the point itself) and short enough so that the identified point maintains its characteristics in order to be recognised in subsequent images as the same point seen in earlier images.

In order to test the PIV method the UAV was flown above various locations on the Cam where the flow was considered fast enough to reliably detect. The UAV was positioned so that the boundaries of the image frame where fixed object (e.g. river walls or bridges) and then kept as still as possible. Video was then taken for use with the PIV software. Some flights were conducted with the UAV simply videoing the river flowing normally with bubbles and any natural debris providing identifiable points. Other flights were conducted while debris was added to the flow to provide more identifiable points. Leaves were the debris of choice as they are small and light floating on the surface and not disrupting the flow, whilst also being biodegradable negating the need to pick up the debris after videoing.

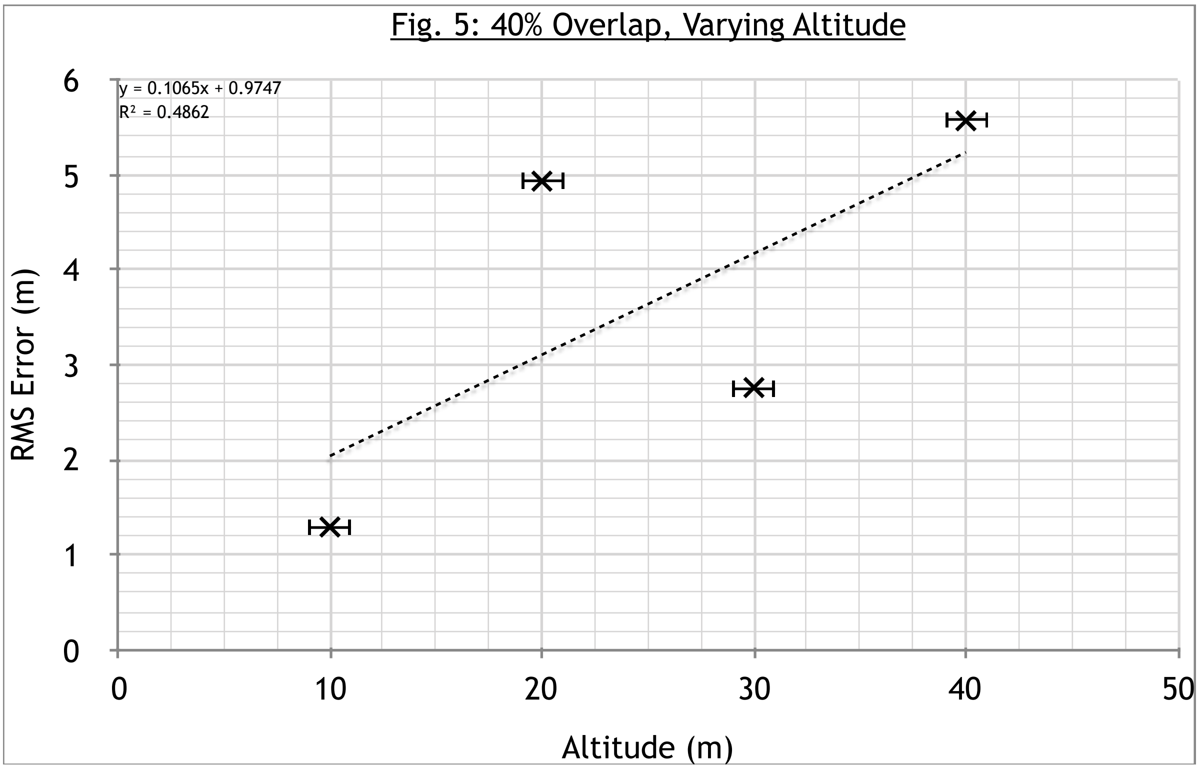
Videos at the busy locations of the Mill Pond and Jesus green were carried out in the early hours at weekends to avoid crowds and the video was taken with the UAV hovering at at least 50m to abide by UAV regulations (not to come within 50m of person or property). Closer range videos were taken at the Rush where the risk of encountering the public was much lower.

5.0 SFM Results and Discussion

5.1 SFM Altitude

At the Technical Milestone report stage altitude was identified as having negligible impact on the accuracy of PIV measurements. However, with the extra flights carried out since to repeat anomalous results and obtain more data within the usable range of flight settings identified in the earlier flights a different picture has emerged. The following graphs show that accuracy does indeed vary with altitude with the RMS error in the vectors between the control points found using SFM compared to the actual vectors determined via traditional surveying increasing with altitude.

(The error bars for altitude are based on observation of the UAV in flight with its altitude consistently within 1m of the desired altitude set. Error bars are omitted for the RMS error as the error is in measurement is what is being determined.)



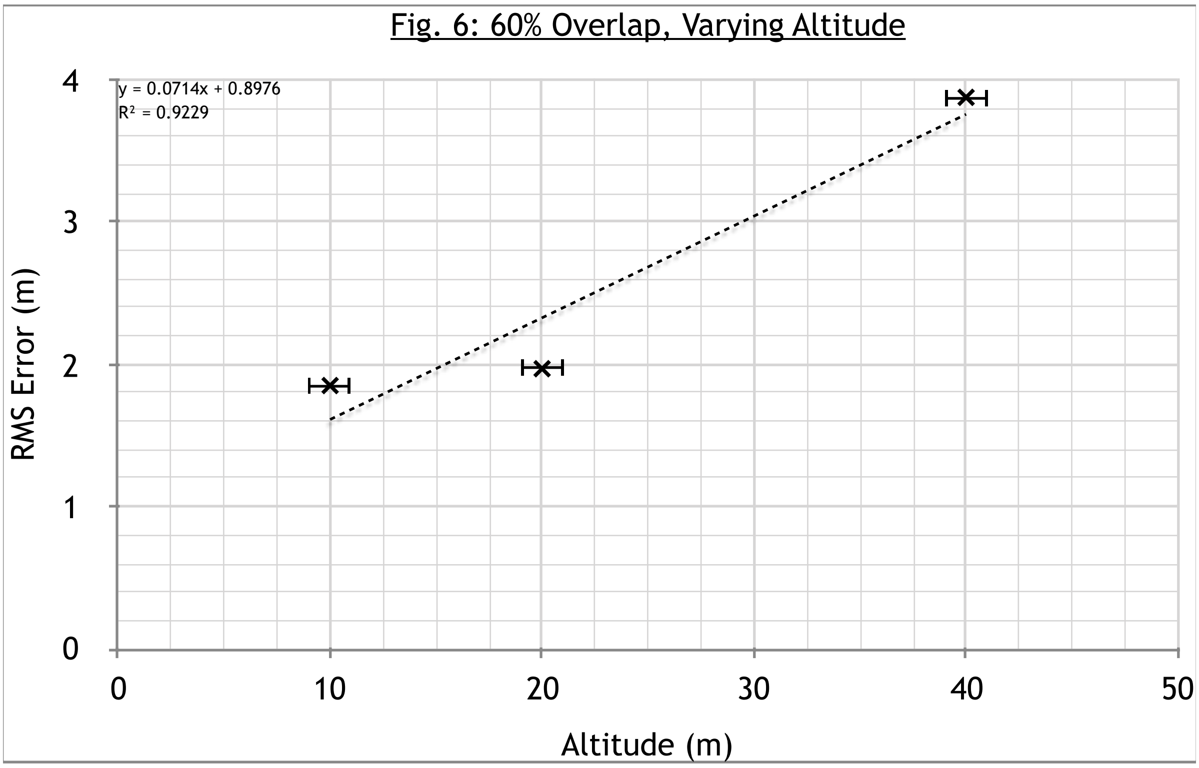


Fig. 6: 60% Overlap, Varying Altitude
y = 0.0714x + 0.8976
R² = 0.9229
RMS Error (m)
Altitude (m)
0
1
2
3
4
0
10
20
30
40
50

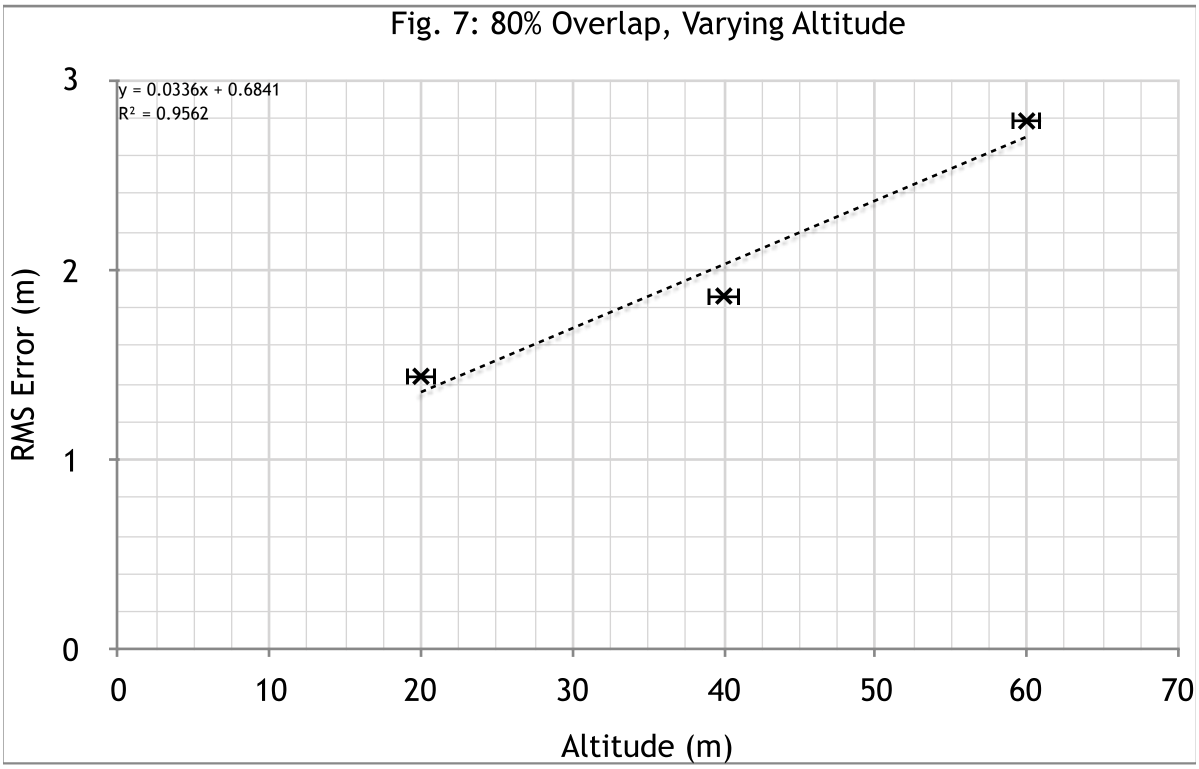


Fig. 7: 80% Overlap, Varying Altitude
y = 0.0336x + 0.6841
R² = 0.9562
RMS Error (m)
Altitude (m)
0
1
2
3
0
10
20
30
40
50
60
70

All three graphs reflect the result that the error increases approximately linearly with increasing altitude. This affect is present independent of the overlap, although the influence of overlap can still be recognised: the variability and magnitude of errors is significantly less at 60 and 80% overlap than at 40%. The overlap appears to have a more significant impact on the accuracy of the SFM measurement, which may explain why the smaller impact of altitude was not detected in the preliminary testing as outlined in the technical milestone report.

A perhaps more important reason for this is that increasing the the altitude can have the inadvertent effect of increasing overlap if the survey area is small. When using the Pix 4D app to pre-program UAV flights a target overlap is set and the planned flight takes an appropriate number of photos to cover the designated survey area. However, if the survey area is small and the flight taken at a higher altitude then every photo will cover most of the survey area and so even with a minimum number of photos overlap values will still be high. Using the number of matched points as a proxy for overlap is not an option either as we have shown this is also dependant on altitude. In order to avoid this interaction we discounted earlier results at higher altitudes and carried out more tests in the range 20-60m.

Rather than looking at results for altitude at varying overlaps distinctly, taking an alternative approach to controlling for overlap and simply averaging results for different altitudes across different overlaps also yields a clear linear relationship as shown in fig. 8.

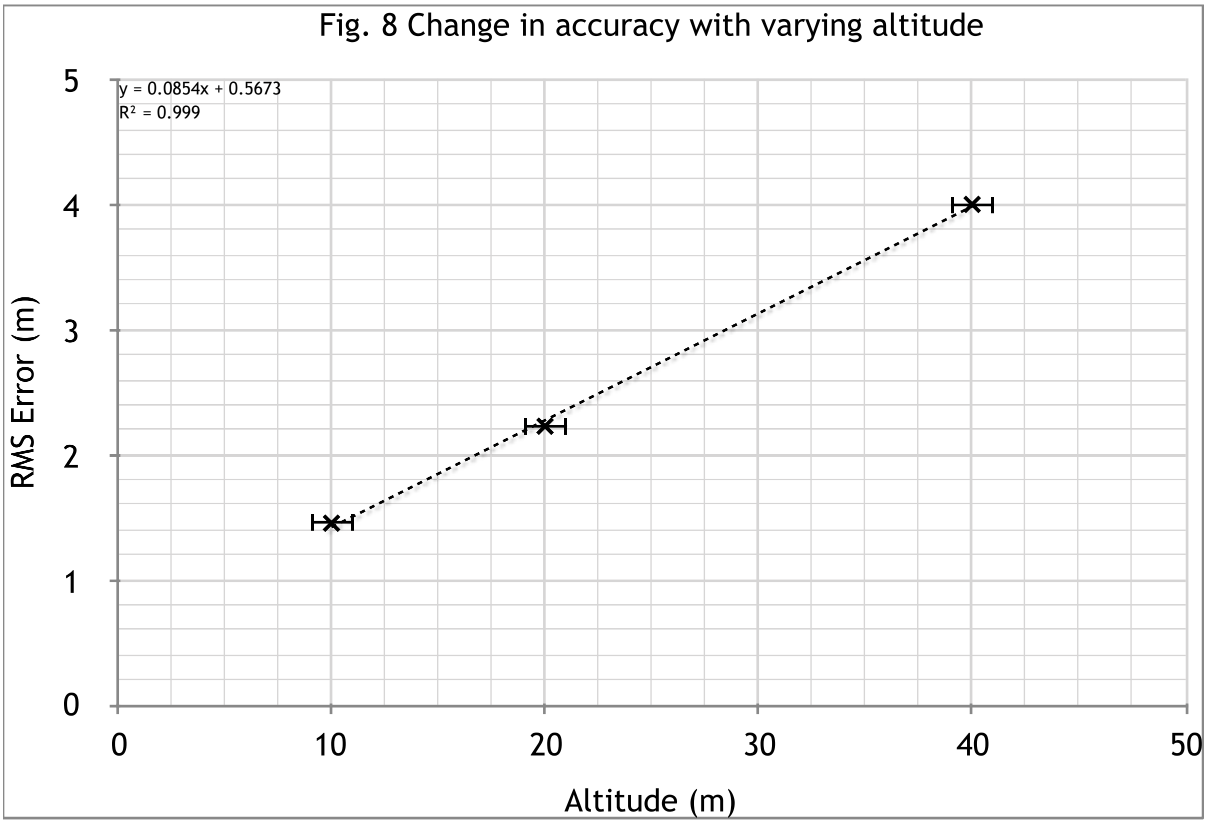
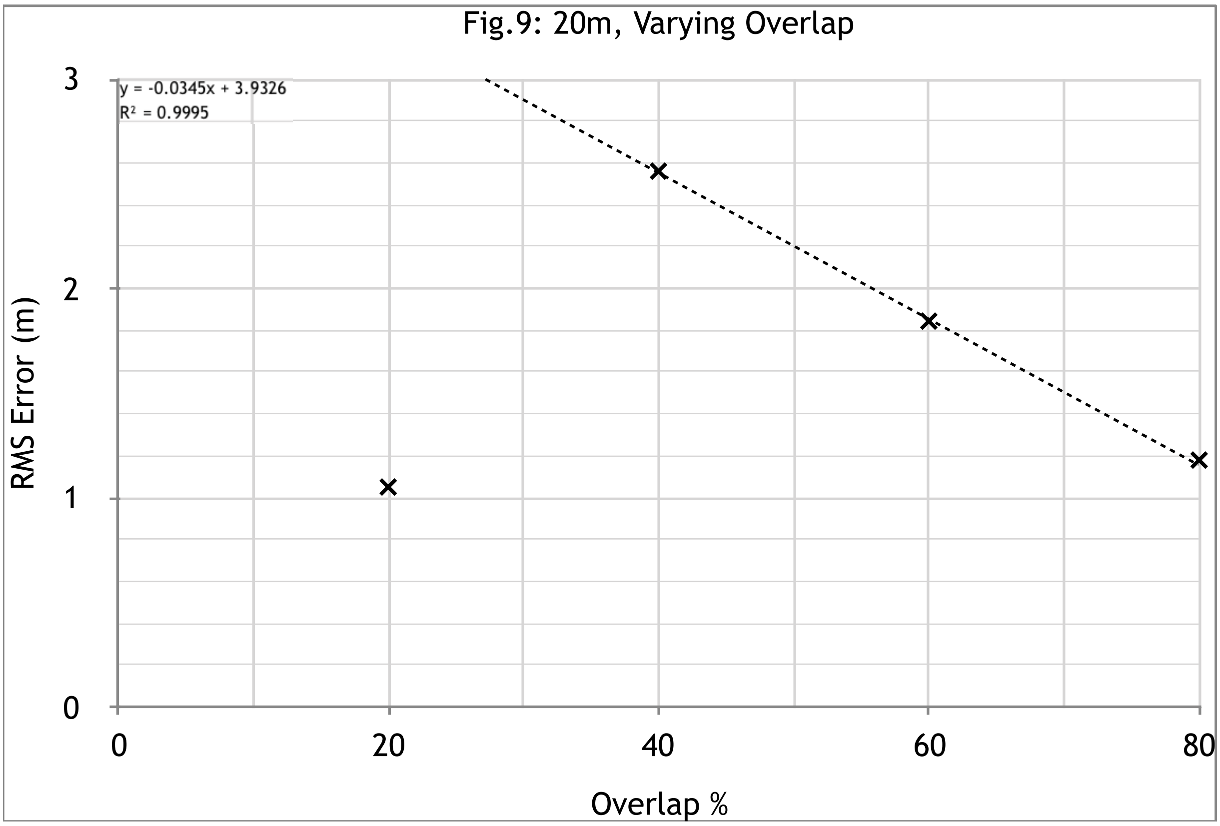


Fig. 8 Change in accuracy with varying altitude
y = 0.0854x + 0.5673
R² = 0.999
RMS Error (m)
0
1
2
3
4
5
0
10
20
30
40
50
Altitude (m)

5.2 SFM Overlap

Further testing has confirmed that overlap has a strong influence on accuracy with RMS error in the calculated vectors between control points reducing linearly with increasing overlap. Fig. 9 and 10 show this approximately linear trend but also the still high variability in results with the readings at 20m in Fig. 9 and at 40% in fig.10 appearing some way from the general trend. This likely in large part due to the still relatively small data set at specific altitudes (or overlaps). Using all available data across the full range of altitudes and simply averaging produces a clear linear relationship between overlap and accuracy (Fig. 11).



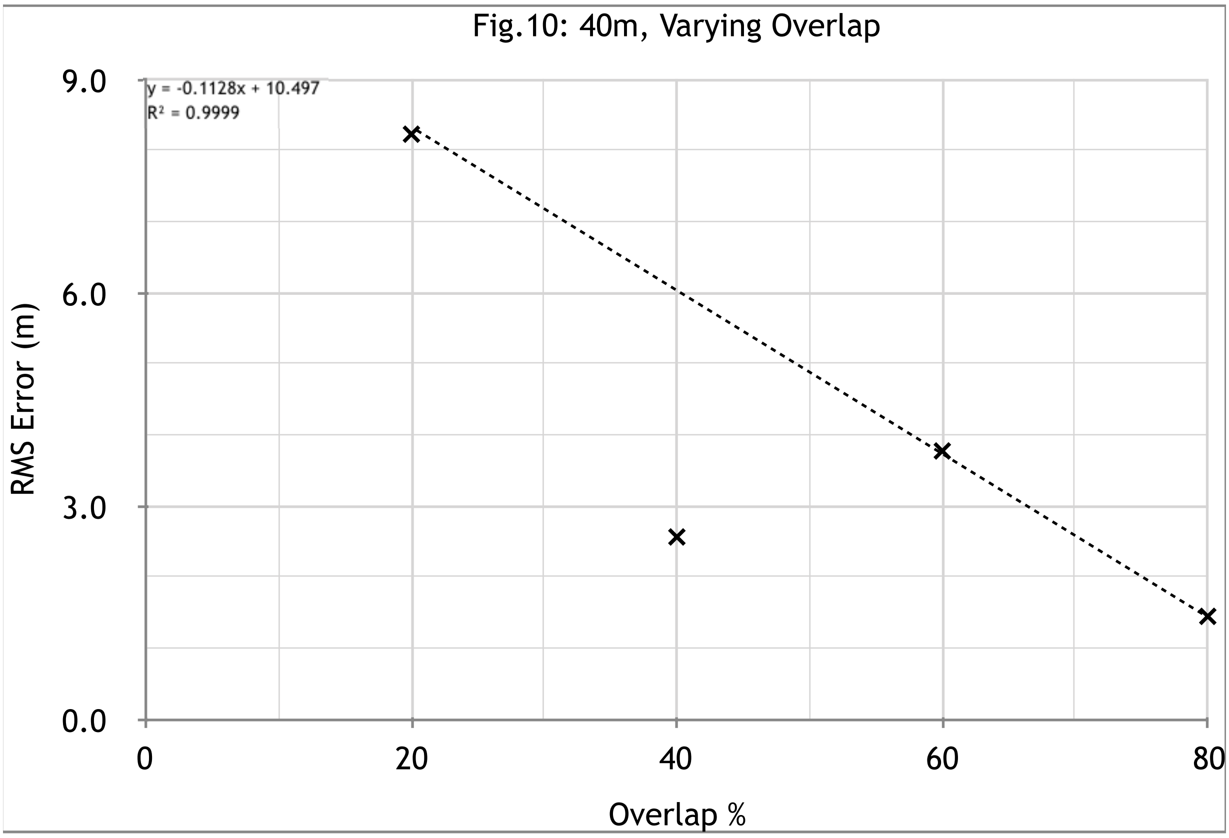


Fig.10: 40m, Varying Overlap
y = -0.1128x + 10.497
R² = 0.9999
9.0
6.0
3.0
0.0
RMS Error (m)
0
20
40
60
80
Overlap %

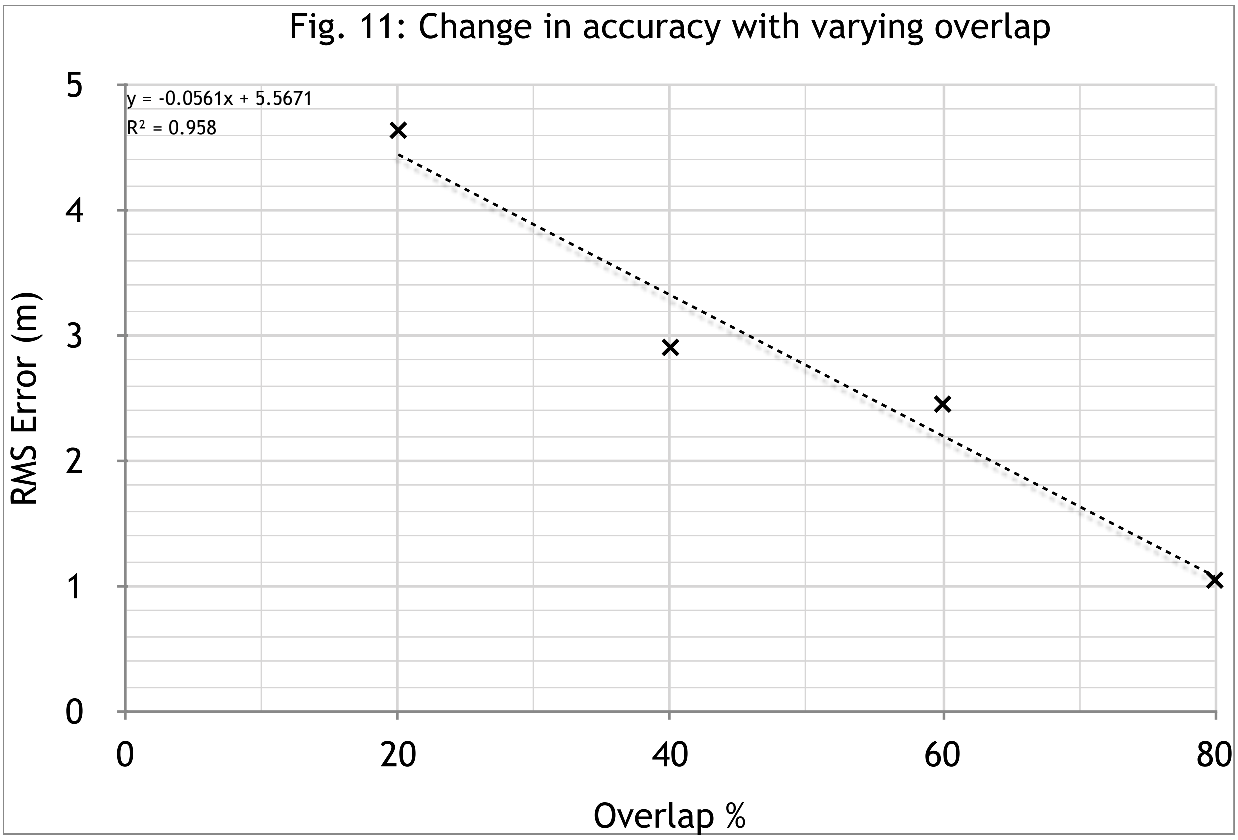


Fig. 11: Change in accuracy with varying overlap
y = -0.0561x + 5.5671
R² = 0.958
5
4
3
2
1
0
RMS Error (m)
0
20
40
60
80
Overlap %

5.3 SFM Overall Accuracy

Having shown that accuracy of the SFM technique is related proportionally to overlap and inversely to altitude its accuracy relative to other techniques is also necessary to make a judgement on its utility. This needs to be taken in the context of the effect altitude and overlap on flight times. Flying at lower altitudes means more photographs are required to cover an area at a given overlap and increasing the overlap also increases the number of photos required. Both follow a power law relationship and more photos means longer flight times (see fig. 12 and 13 below):

Fig. 12 Altitude (m)	Flight Time at 50% overlap for 100m^2 area (mins)
10	21
20	7.5
30	5
40	4

Fig. 13 Overlap (%)	Flight time at 20m altitude for 100m2 area (mins)
20	5
40	6.5
60	10
80	26

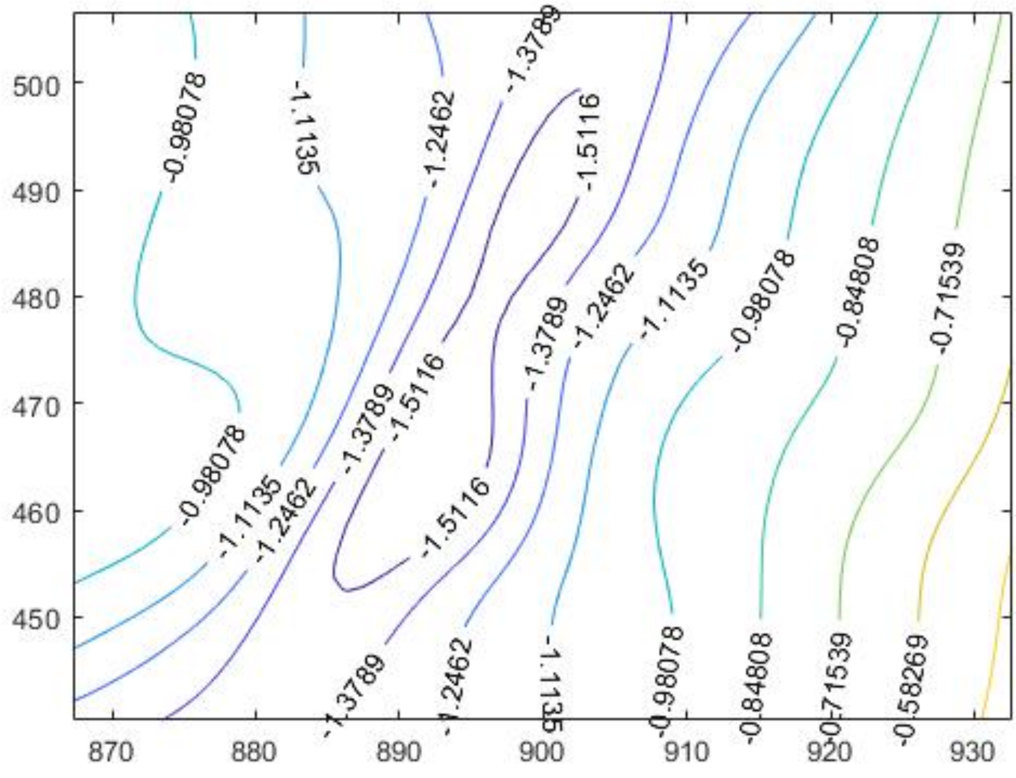
The effect on processing times is even more pronounced with the most demanding part of the SFM processing being to bundle adjust every matched pair of images together and then combine with GPS camera positions to find the best solution. The run time here is also a high power relationship. With the Phantom 4 Pro UAV battery life of around half an hour this limits any reasonably sized survey to fairly modest altitude and overlap settings.

However, even with time restrictions the UAV enabled SFM method can stand up well. Averaging across all results from the lent tests which were carried out between 20-60m altitude and 40-80% overlap the RMS error in the 3D vector between control points was 2.6m. Breaking down in x, y and z directions reveals that the average elevation (z) error was 0.4m, whilst in the plane of the ground the average error was 1m. However, bearing in mind the average distance between control points was around 20m, while the variation in height was only around 0.5m, the percentage error in height was much greater.

Lidar surveys (the most commonly used data source for floodplain mapping) commonly have RMS errors in elevation of between 0.26 and 1.53m, usually with a resolution of around $2m^2$ [7] This places our UAV SFM technique comfortably within this range. The detail obtained through SFM is also much higher with the point cloud picking out features only centimetres in scale although the accuracy of such identifications can be questioned.

Once obtained the point cloud can be exported quite straightforwardly and used in flood modelling software, although some further processing may be required depending on the desired format of the elevation data. Figure 14 below shows the contour map produced from the Pix 4D point cloud using Matlab's contour function.

Fig. 14 Contour Plot, Coe Fen Ditch Flood Plain



The majority of the area surveyed in these tests was over grass. However, ground texture was considered as a possible influence on the overall accuracy of the SFM technique. Texture clearly had an effect on the number of identified points in any image. The difference between the mostly rough grass of our test area and those areas regularly trodden on were clearly visible in the point cloud data. The density of points identified in the trampled zones of grass (i.e. along paths) were approximately halved and even further reduction in numbers of points where seen on solid surfaces. However, the density of points was still greatly in excess of that needed to successfully find an accurate elevation model and the continuity in points between path and ground suggest no loss in accuracy.

So long as a surface has at least some identifiable features the technique works well, the only surface with effectively no points was that of the water. There may be some worry over large uniform man made surfaces such as car parks or roads but these certainly have easily identifiable points in form of road markings or joints etc. and although these are quite widely spaced the variation in height between them tends to be relatively small and crucially regular, so the loss in density of points does lead to the loss of features in the ground elevation.

The one ground coverage that does pose an issue to the photogrammetry technique is that of dense vegetation. Using standard photos does not allow any penetration through foliage cover unlike Lidar where varying laser wavelengths and penetration of vegetation is possible. This makes UAV based surveying inapplicable to forested areas although it is highly applicable to urban areas where flood risk modelling is arguably most essential.

6.0 PIV Results and Discussion

6.1 Stabilisation

Initial PIV tests were not particularly successful. Whilst the video captured by the UAV appears stable in real time viewing when adjusting between images it becomes clear there are numerous movements (unsurprising given the wind conditions at 20+ meters altitude even on a still day). It had been hoped that stabilisation of the images taken from the video would be possible through the use of software rather than relying on the hardware fo the drone to provide a stable platform. Various programs are available for this purpose but all of them, ranging from self made to the latest Matlab add on struggle with producing a consistently stable image from the UAV video. Between subsequent frames the effect is very reliable (which of course is all that is required for viewing video) but over the longer time differences needed to get useful results from a relatively slow flow the small translations, rotations and changes in height of the UAV add up to change the image enough to make fixing the image precisely possible.

All the stabilisation methods follow approximately the same routine, identifying stationary objects in the field of view and then transforming one image so they remain stationary between images. The stationary objects can either be identified manually by the user or automatically by finding many points in the field of view that move by the same amount between frames. This means if the flow that is being measured is close to the speed of movements in the camera position then is becomes very difficult to distinguish between stationary and moving objects.

6.2 Targets

The second issue with the PIV method was the provision of identifiable points. The glassy surface of even disturbed water certainly does not them with enough regularity. The addition of targets to the flow (e.g. leaves) did yield some results but obtaining a full coverage of the flow is difficult both in terms of coverage but also the propensity of debris to be drawn to high flow areas leaving the low velocity regions of the flow unrecorded.

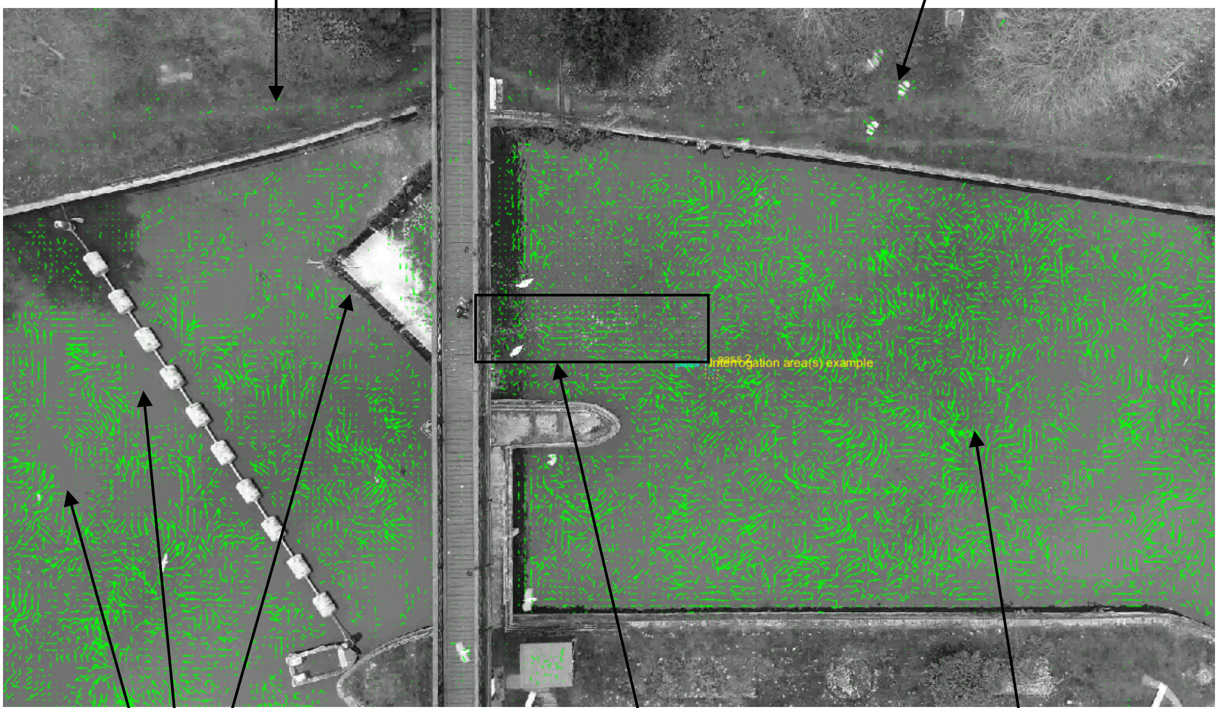
6.3 Jesus Lock Example

Figure 15 below is an example of the PIV analysis obtained at Jesus Lock. Various features are identified, length of the green arrows indicates speed:

Movement identified in stationary areas, various directions shows lack of stabilisation

Fig. 15

Velocity of birds picked up within analysis, where these are over areas identified as stationary can interfere with stabilisation



Zones of “no movement” in areas where no identifiable points, notably at floats and wire where debris is blocked despite flow being accelerated

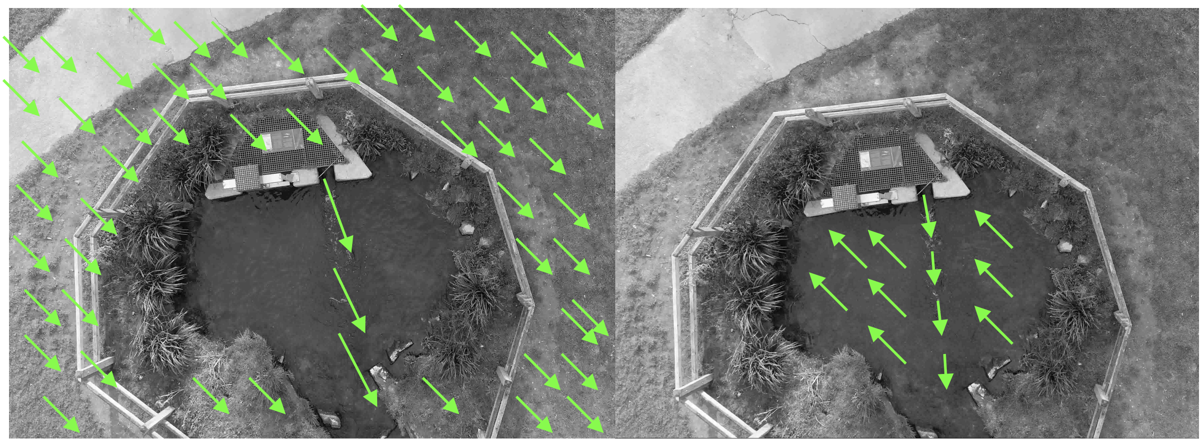
Region of clear aligned flow at exit from weir, where there is a clear and crucially quick and frothy flow, shows potential of PIV with high flow and identifiable points

Chaotic direction of “flow” and velocities higher than exhibited in actual flow. This may be due to vibrations or sudden movement of the camera

6.4 The Rush Example

Below are two images of the entrance to the Rush following stabilisation. This test location yielded far better results. Firstly the area surveyed is far smaller at only a few meters across unlike the Jesus lock example at scale around 10 times larger. This meant the UAV could also be flown lower (with less variable wind conditions and below birds). There is also a greater proportion of the field of view stationary between frames which may have aided the stabilisation. Crucially the surface velocities in the high flow region are much higher than any movements of the UAV and there was a consistent production of bubbles providing easily identifiable targets. Scaling the image using the distance between fence posts gave a velocity of the fast flow region within 10% of that measured with a flow meter (just below the surface). Before obtaining this result was obtained further processing of the PIV results was required. In figure 16 below the image on the left shows a sketch of the velocity field initially calculated: there is clearly a drift between images, after subtracting this drift from the velocity field the field indicated on the right was obtained. This gave a good estimate of the flow in the high velocity region but now shows the low velocity areas having a flow in the opposite direction to the camera drift. This could also be corrected for but the more areas selected manually to adjust the field the longer post processing becomes. For a larger region this is not really feasible.

Fig. 16, The Rush PIV Example



6.5 Comparison to other studies

The PIV results appear discouraging but this should perhaps have been expected looking at previous attempts. Tauro et al. (2015) managed to produce stable images from a UAV but only over an area of $1m^2$. Patalano et al. (2015) used UAV based PIV at a much larger scale measuring the discharge of rivers in flood and since developed the RIVeR software which was used on some iterations of this projects testing. They achieved estimates of the river discharge within 1% of the true value measured with an acoustic Doppler current profiler method. However, the velocities present in this study are far in excess of any available to us during this project. Other tests using shock absorbing gimbals with a larger UAV or even helicopters have also been more successful in lower velocity flows but start to defeat the purpose of finding a low cost alternative to existing techniques. [3]

Gabriella Lükő [3] carried out more similar experiments to our in 2016. Similar issues can be identified although her velocity field measurement where arguably more successful (see fig. 17 below):

Flow is well described around the obstruction, where velocities are high and foam is generated providing identifiable points. Rest of flow is patchy and does not match velocities obtained through ADCP.

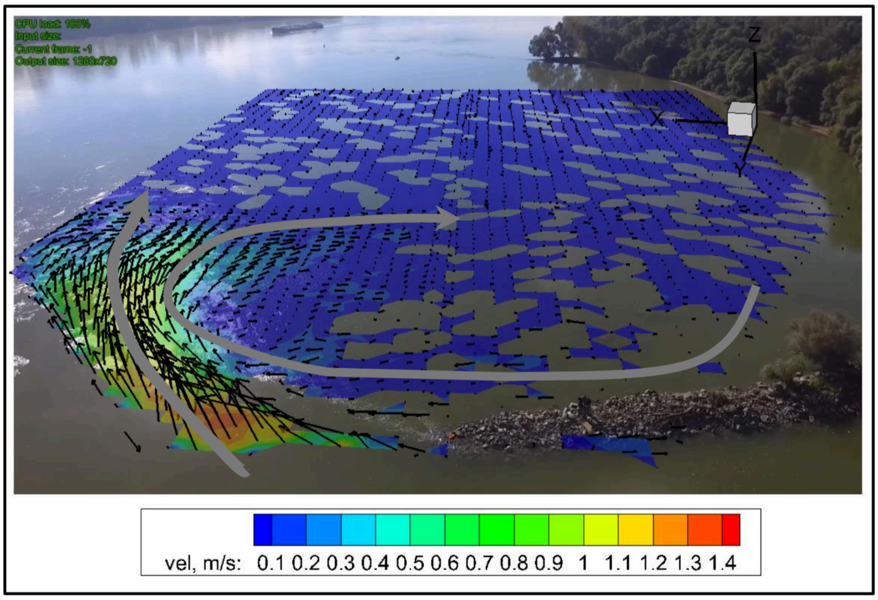


Fig. 17 [2] *Surface velocity distribution near the groynes from UAV-based LSPIV measurements (perspective view)*

7.0 Other Considerations

7.1 UAV Restrictions

Beyond the accuracy, usability and cost concerns discussed so far in this report there are other restrictions using UAVs that need to be considered in their applicability to hydraulic surveying.

Firstly the regulations surrounding the use of drones. The main restriction is to keep 50m from person or property. Whilst flying at at least 50m altitude to meet this restriction in relation to people on the ground is not particularly damaging to surveying attempts, in built up areas buildings, plus the 50m limit, can force the flight plan up to significant altitudes, where as discussed in section 5.1 reduces the accuracy of data collected. Conversely there is also a maximum altitude for UAVs of 120m. Whilst the flights conducted in this project at that altitude tended not to produce usable results with a higher resolution camera and possibly larger more stable UAV platform altitudes significantly higher than this may be optimal for surveying purposes, as so long as the accuracy reduction due to altitude can be kept within acceptable limits much greater areas can be covered at a suitable overlap value in a much shorter time. This is obviously desirable for hydraulic surveying where floodplains can cover many kilometres of ground and models must be regular updated.

There are also considerations to be taken into account flying near airports. Currently no UAV flights are permitted within 1km of airports, which is not a particularly restrictive regulation. However, following events at Gatwick there are plans to increase this to 5km, which if implemented in full would have made this project impossible, although plans to make this a 1km wide corridor extending 5km along the axis of the runway would have allowed most areas of the cam to be surveyed. [8]

Exemptions from certain regulations can be obtained for certain purposes but this adds a level of complexity and cost that starts to erode the UAV based method's advantage over more complex costly alternatives. As UAVs become more common regulation is only likely to increase potentially making this technology less useful.

7.2 Satellite Photogrammetry

At the Michaelmas presentation the possibility of utilising satellite images to carry out Structure From Motion mapping was suggested. Accessing a suitable number of satellite images of the same location at a close enough time spacing and all with location data proved difficult. However, google has been using photogrammetry with its extensive satellite image database for some time to provide 3D building models as well as landscapes to view on its Google Earth and now Maps platforms.

The problem with satellite image photogrammetry is the baseline error can be extremely significant. At very high altitudes the angle between ray lines from different camera positions to identified points becomes very small and this leads to large errors in elevation measurement, since small deviations result in large changes in the measured height. Also with images taken from such a great distance the area represented by each pixel is much larger (even with higher resolution cameras). Therefore point identification with smaller features can be harder leading to a loss in resolution of the elevation map.

The result is SFM measurement from satellites is good enough to produce realistic 3D models and impressions of the landscape for use in google earth and maps. An RMS error of 2.3m in elevation across the USA road network also makes google earth a useful tool for lorry route planning [6], however, this kind of accuracy (which worsens away from the USA and away from regular features like roads) is not good enough for hydraulic modelling although could be used to give a good impression of the watershed areas for river basins where the height variations are greater.

8.0 Conclusions

This project has demonstrated the potential utility of using UAVs in conjunction with photogrammetry to undertake hydraulic surveying. In particular the Structure From Motion technique, which with the appropriate flight settings (altitude 20-60m, overlap 60-80%) produced results with accuracy equal to or better than LiDAR surveys, which are the current main source of ground elevation data. When planning hydraulic surveys of floodplains using SFM the surveyor should strike a balance between time and accuracy, with increasing overlap and decreasing altitude simultaneously improving accuracy whilst increasing flight times and processing times.

With the equipment available in this project flight time was the main restriction with the Phantom 4 Pro drone's battery life limited to approximately 30 minutes. To carry out an effective survey overlap should be maximised and altitude minimised whilst covering as much of the survey area as possible. Multiple flights with battery changes will be required to map large areas. Similar to many other technologies a significant improvement in the charge/weight ratio in batteries would transform the utility of UAVs. There was an opportunity to use a larger, longer battery life, student built drone for this project, but the set up of control software and camera positioning would have limited the tests we could carry out. However, with some adjustment such a UAV could greatly improve the performance of UAV SFM. The SFM technique worked well on a variety of surfaces with the exception of dense and tall foliage, in forested areas the technique will not be suitable to displace current methods but in cities provides an excellent alternative.

Satellite based photogrammetry is eminently possible and already utilised to great effect by Google and others in GIS applications but lacks the required accuracy for hydraulic surveying at least as far as flood plain mapping is concerned. At present the regulations surrounding UAV use are fairly relaxed and pose few problems to surveyors besides avoiding busy times in urban areas and forcing higher altitude flights (which can be compensated for with greater overlap). However, these regulations are likely to become stricter posing a potential threat to this technique.

Particle Image velocimetry testing was less successful. While UAV based PIV can produce reliable results for either very small scale survey areas or very high velocity flows (such as in flood conditions) their utility to measure river flows in normal flow conditions is limited. Floating targets are really required to comprehensively map a flow and for large scale studies the quantity of debris added to the water may not be particularly attractive. More crucially stabilising the video taken from a UAV at any significant altitude (required to capture a significant survey area) proves difficult, as the UAV may not only translate in the air but also rotate, change altitude and vibrate/shake.

UAV based PIV can be very useful for surveying extreme flow conditions, useful information can be gathered and here the UAVs ease of use, speed to put into operation and ability to quickly cover a wide area become particularly useful. This functionality has been demonstrated by others. However, for general hydraulic surveying of medium size rivers in normal flow conditions (as investigated in this project) its utility is limited.

The whole process surrounding surveying is time consuming and this is still evident with UAV photogrammetry. Planning and then carrying out flights requires significant man hours particularly as a UAV must be monitored on the ground by an operator while it is in use. Processing of the thousands of images in a typical survey also takes many hours and post processing operations and analysis are also lengthy. However, in comparison to traditional surveying and even more modern methods including Lidar the turn around time from sure planning to useable results is still quick and costs are dramatically lower.

To improve this further and perhaps make PIV surveying more accurate larger UAVs should be tested, able to carry bigger batteries and with more stable flight, improving flight times and stabilisation of images.

9.0 Risk assessment retrospective

The risk assessment carried out at the start of this project correctly identified the direct risks associated with the drone: lithium batteries, rotors and debris and the protection measures put in place to protect mainly the operators, i.e. myself and my project partner , where suitable and sufficient. Diligently checking all equipment and batteries before each use meant we experienced no problems in that regard. Taking the time in the first weeks of the project to learn how to fly the drone manually and familiarise ourselves fully with the control software also proved invaluable and during later tests the drone stopped responding but we were able to safely guide it to the ground to be reset.

However, the risk assessment produced failed to clearly mention the risk of the UAV running out of battery power mid flight. This was highlighted by Dr Chen and throughout our later tests a strict lower limit of 30% was applied and the UAV brought back to the ground if the battery level dipped below this level. This restricts the amount of data that can be collected from each battery charge but depending on wind conditions significant battery can be used up in landing. Further batteries were purchased to enable more efficient data collection and had we identified this risk earlier they could have been procured earlier, accelerating data collection.

The risk associated with members of the public was highlighted in the original risk assessment, although this focus purely on the risk of injury with control measures based on complying with regulations and keeping a safe distance from passers by, busy times at busy locations (Jesus lock and the Mill) were also avoided, with early morning weekend flights. However, we did not consider that some members of the public may be concerned about our intentions flying the UAV near them or property. Many members of the public were simply interested and approached us to ask about our work but some assumed we may be taking photographs of people and asked to be excluded before we explained our work. Flying near The Leys School in particular prompted concerns around safeguarding. These were quickly resolved with a conversation with an official from the school but earlier identification of this risk could have avoided any unnecessary interaction.

10.0 Sustainability Considerations

UAV photogrammetry has the potential to have a very positive sustainability impact. As we have shown its comparable accuracy to LiDAR measurements which use laser equipped aeroplane flights, it could potentially reduce the need for such flights which have a significant carbon footprint, although they will still be required over forested areas.

The potential environmental damage of using plastic or painted targets in PIV tests was considered and instead leaves were used. Brightly painted or plastic targets may have been more effective but cannot really be put into the river without being able to collect them. In other studies wood chips have been used to good effect. [3]

The material and energy used manufacturing the drone is small and comparable to that used in the production of traditional surveying equipment. The energy use of the drone itself is very small, with the lithium ion batteries themselves having the greatest environmental impact in terms of manufacture and disposal.

11.0 References

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12.0 Acknowledgements

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