Paper presented at ISASI 2016 Seminar, October 2016, Reykjavik, Iceland

Using a drone and photogrammetry software to create orthomosaic images and 3D models of aircraft accident sites

By Stuart Hawkins, Senior Inspector of Air Accidents (Engineering) at the UK AAIB

Stuart Hawkins is a Senior Inspector of Air Accidents (Engineering) at the UK Air Accidents Investigation Branch (AAIB) where he has worked for the past 14 years. During this time he has investigated over 190 accidents and incidents, including over 60 field investigations. Prior to joining the AAIB he worked as a Flight Test Engineer and Aerodynamics Engineer for Boeing in Seattle and a Flight Test Engineer for DERA/QinetiQ at Boscombe Down in the UK. He has an honours degree in Aeronautical Engineering, a Private Pilot's License with multi-engine and instrument ratings, and is an AAIB-authorised drone operator. He led the AAIB's project to procure the first drones, helped to develop safe operating procedures for them, and he introduced photogrammetry software to the AAIB.

Abstract

Drone technology has developed significantly in recent years. Lightweight quadcopter drones with quality cameras are now very affordable. The UK AAIB has been operating drones at aircraft accident sites for over 2 years and has used them at 23 different accident sites varying from fields to major airports.

This paper presents some examples of images obtained by AAIB-owned drones that would have been difficult to obtain by other means, such as the tops of broken trees and wreckage below a cliff in poor weather. It is less expensive to use a drone for accident site aerial imagery than a helicopter and the images can be obtained quickly, within minutes of arriving at an accident site.

This paper also presents how photogrammetry software can be used to process drone images to create geo-referenced maps, orthomosaic images, and 3D visualisations of an accident site. This is a new technique and the AAIB has used such software to create 3D 'point-cloud' models and orthomosaic images of two large accident sites. The photogrammetry software enables measurements of a site to be taken that can be up to 1 cm accuracy using drone imagery alone. This paper presents some of the lessons the AAIB has learnt from using this software, and presents some examples of measurement accuracy from accident sites and from separate trials.

The combination of drone imagery and photogrammetry software provides a very useful new tool and link in accident site documentation and analysis, and at a much lower cost than hiring a commercial helicopter or using laser scanning equipment.

Introduction

Aerial images of accident sites are very useful for a number of reasons. They can capture the whole site from the initial impact point to the wreckage's final resting location; and the ground marks and wreckage distribution help to identify how the aircraft hit the ground. They are also useful for showing the relative positions of obstacles, such as trees or buildings, which may have been struck before ground impact. They help to reveal the surrounding terrain and environment that the pilot would have faced if it was an attempted forced landing. And when it's a large aircraft at an accident site, aerial images help to document the damage to its upper surfaces.

In the past the AAIB has been primarily reliant on police helicopters and sometimes search and rescue helicopters to obtain aerial images. These images have been useful but did not always capture the angle or detail we wanted and often we would not receive the images until a week or more after the accident. There has always been the option to charter a helicopter but this is expensive and can take time to organise, when the priority is usually to clear the accident site as soon as possible.

About 3 years ago I noticed that small Unmanned Aerial Vehicles (UAVs), or drones as they're now more commonly referred to, had become significantly less expensive and could provide us with aerial images within minutes of arriving at an accident site. And by controlling the drone's camera ourselves, we could capture all the angles and details we needed.

We bought our first drone, a DJI Phantom 2 Vision (P2V) for £832, in February 2014, and first used it at an accident site on 14 March 2014 (Figure 1). Its 14 megapixel camera provided excellent stills although the video quality was shaky due to a lack of a gyro stabilised mount. We used it at 5 different accident sites. After the DJI Phantom 2 Vision Plus (P2V+) (Figure 2), with a gyro stabilised mount, was released in April 2014, we upgraded to it 3 months later and have used it at 11 accident sites. As well as taking stable video the additional benefit of the P2V+ was that the camera could be tilted 90° downwards to take a series of overlapping images to map the whole accident site. I was expecting to be able to use photo-stitching software to stitch all the images together but I couldn't get it to work. The trials we did were of objects laid out in fields, and the lack of variation in the images, because they were mostly of green grass, was beyond the photo-stitching software I tried. Even if it had worked the stitched image would not have been to scale. Photo-stitched images usually have some distortion and are not true to life. This led me to examining what photogrammetry software could do, and I learnt that not only could it generate 3D models from a series of overlapping images, but it could also create a stitched overhead image that was true to scale; an image which is called an orthomosaic. The photogrammetry software we ended up buying is called Pix4Dmapper Pro and the details in this paper refer to the capabilities of this software. We obtained some good photogrammetry results using the P2V+, and then in September 2015 we upgraded to the DJI Inspire Pro (Figure 2) which can operate in winds up to 20 kt and has a higher quality camera that can stream HD video to two tablet devices. It is also available with dual controls for the pilot and camera operator.

Figure 1
First use of the AAIB's Phantom 2 Vision drone at an accident site on 14 March 2014

Figure 2
DJI Phantom 2 Vision Plus (left) and DJI Inspire Pro (right)

How the AAIB operates its drones

Under UK regulations the AAIB can operate its drones at accident sites under the standard regulations for recreational users, because we are not classed as a commercial operator flying for reward. The main limits are maintaining visual line-of-sight, a minimum distance of 50 m from people, buildings and vehicles that are not under our control, and 150 m from congested areas. Since we primarily operate inside a police cordon where everyone can be under our control, these limits have not restricted our operation. We have an operations manual which lists flight limitations and training and currency requirements for our operators. At the moment we have two main operators and they are our engineering support staff. One of them will normally deploy to an accident site to assist with wreckage recovery and they will fly the drone. The engineering investigator onsite will normally operate the camera. The AAIB requires two people to operate the drone, because to fly the drone safely the pilot needs to be heads-up watching the drone and looking out for obstructions and people; while to take good pictures you need to be heads-down. The only time single operator flight is allowed is when the drone has been programmed to fly an automated route and automatically take stills; in this case the operator is monitoring the flight and is able to override the autopilot.

Benefits of drones for accident site imagery

The benefits of using drones over manned aeroplanes or helicopters are:

- Significantly lower cost (a suitable drone can be obtained for £700[1])
- Drones can be deployed immediately on arrival at site
- The images and video from the drone can be viewed live on the ground
- The engineering investigator has full control over the images and videos that are taken
- A drone can be easily re-launched to take additional footage
- A drone can be flown closely to trees and wreckage to obtain close-up images without disturbing them with rotor downwash
- A drone can be easily programmed to take a series of geo-tagged and overlapping overhead shots for photogrammetry purposes
- A drone can operate in low visibility and low cloud conditions that would prevent an aeroplane or helicopter being operated

Drones do have their limitations though. The DJI drones that the AAIB operate cannot be flown in rain and struggle in wind above 20 kt. Higher performance, water resistant, drones are available but at the moment they cost significantly more than the £3,300 DJI Inspire Pro. To avoid conflict with manned aircraft, drones should not be flown above 400 ft agl which means that if a higher perspective view of a site is needed, a manned aeroplane or helicopter could still be required. Battery usage is another limitation. Depending upon conditions the low battery warning can come on after just 15 minutes with the Inspire Pro, but with 3 batteries and a vehicle charger this limitation is reduced. We cannot use our drone in a congested area; however, most light aircraft fatal accidents occur in rural areas so this has not been a limitation yet. Some drones have geo-fencing which prevents you from flying them in certain areas such as over major airports. This affects DJI drones although the AAIB has obtained unlock codes from the manufacturer which enables us to fly at major airports.

The uses we have identified for drones at accident sites are as follows:

- Wreckage and site survey
- Wreckage search
- Tree/object height estimations
- Site safety assessments
- Flight path reconstruction/visualisation

Wreckage and site survey

The most useful aspect of the drone is for obtaining images and video for general wreckage and accident site survey as in Figure 1. When combined with photogrammetry software (as discussed later in this paper) a digital image site map can be obtained. Figure 3 is an image from our P2V

[1] The DJI Phantom 3 Professional (the replacement for the P2V+) with a camera that records 4k video and 12 megapixel stills currently retails for £700. This drone can also be programmed for automated flight for photogrammetry purposes.

drone which shows the tree branches that were broken by a microlight trying to land. It was not possible to see which branches had broken from the ground, and knowing where the branches have broken can help to determine the aircraft's impact attitude. Additional close-ups were also taken which would not have been possible to obtain from a helicopter due to the downwash affecting the trees.

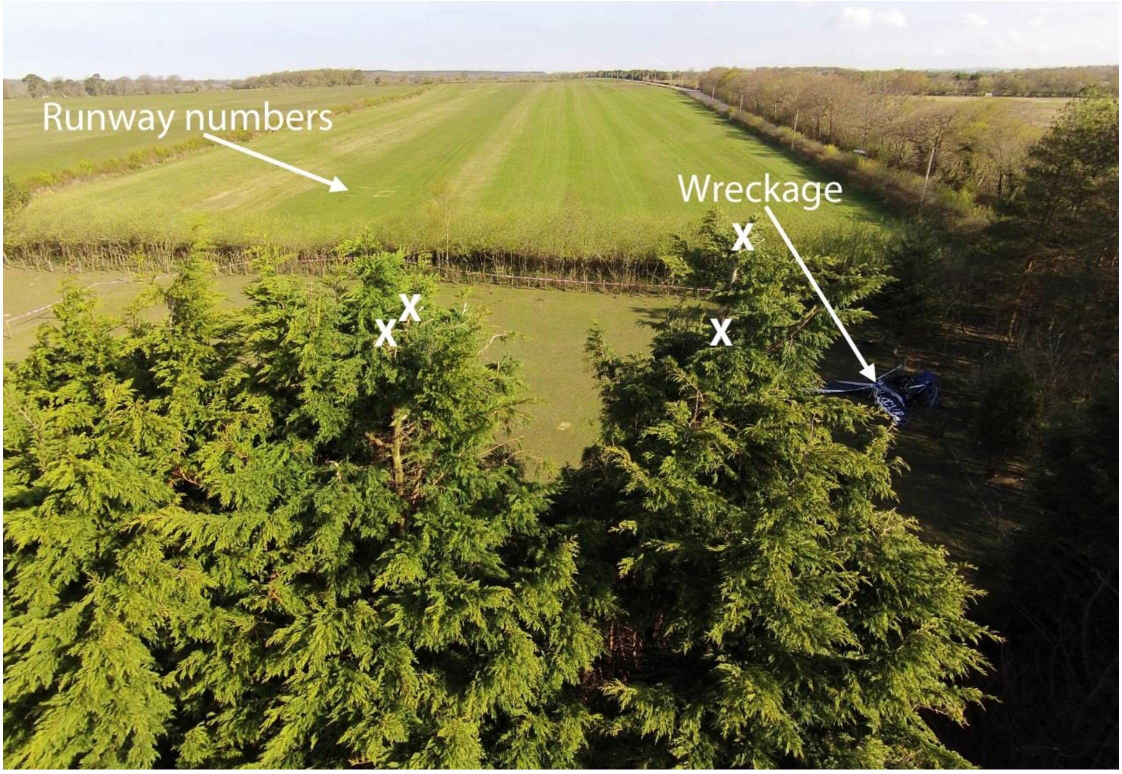


Figure 3

Image from Phantom 2 Vision drone showing broken tree branches (X's), microlight wreckage and runway location

A drone is particularly useful to document debris and marks on a runway when the aircraft needs to be cleared quickly. Figure 4 is an image from the P2V at East Midlands Airport, UK, after a Boeing 737 suffered a left main landing gear failure. The accident caused the single-runway airport to be closed so we were able to operate our drone safely.

Figure 4

Image from Phantom 2 Vision at East Midlands Airport. Note the white scrape marks from the left engine nacelle. The curved horizon is a result of the fish-eye lense on the P2V but this can be corrected using Adobe Photoshop and a lense correction profile.

Wreckage search

The ability to search for wreckage real-time with the P2V and P2V+ was limited due to the low resolution live video feed. However, with the DJI Inspire, we can now view live HD 720p video which allows smaller objects to be found. This is particularly useful for scanning the extremities of an accident site to check for marks that have not been identified from the ground or to check for any parts that detached in-flight. Figure 5 shows a section of separated aileron (30 cm long) in tall crops that is visible in an image taken from a height of 15 m (50 feet). It can, however, be difficult to see this level of detail in the live feed on a tablet because you cannot zoom in on the live-feed. Bright sunlight can also reduce the detail you can see on the screen, but a low cost solution is to drape a coat over your head and the tablet. After the flight the images can be downloaded to a laptop for a more detailed search of the images using digital zoom. DJI have recently launched a new camera called the Z3 which has a 7x zoom made up of 3.5x optical and 2x digital. This camera is compatible with the Inspire and Phantom 3 and 4 series of drones.

Figure 5
Separated yellow aileron tip (30 cm long) visible in tall crops in an image taken from a height of 15 m (50 feet) – this is a 'digitally zoomed-in' cropped version of the original

Tree/object height estimations

The DJI drones provide a height read-out which is displayed on the tablet device. This is the height above the takeoff point and it is probably calculated using both GPS altitude and the drone's internal barometric sensor. For a rough determination of a building or tree height it is quite quick to fly the drone level with the top and take a reading.

Site safety assessments

We have not yet needed to carry out a site safety assessment with our drone before approaching the wreckage. However, if it was known that there was hazardous cargo or ordnance on board then the drone would be useful to identify the location of these. An increasing number of light aircraft have ballistic parachutes, and these rocket-powered devices can pose a significant hazard if they have not been deployed in the accident. A drone could be used to fly close to the wreckage to identify the location and state of the rocket. On one occasion we have used our drone to increase the safety of recovering wreckage from beneath cliff tops. A Jetranger helicopter had crashed into the sea at the base of steep cliffs. We used our drone to identify the location of the wreckage and to supervise Coast Guard personnel who descended on ropes to recover the wreckage. If they had encountered any difficulties we could have informed the winch operator who could not see them below the cliff edge (Figure 6).

Figure 6
Phantom 2 Vision being used to supervise the Coast Guard recovering wreckage from a Jetranger helicopter in the sea below the cliffs.

Flight path reconstruction/visualisation

Drones also offer a low-cost method of obtaining a pilot's eye view of the aircraft's estimated final trajectory. If the aircraft has crashed following a loss of power, then a video of the final flight path can help to reveal the options the pilot was faced with for performing a forced landing. If the aircraft has hit an obstacle, this view can help to reveal how conspicuous the object was. Since it is quick and easy to relaunch the drone at any time, this view can be obtained at different times of the day under different lighting conditions. The AAIB investigated an accident to a microlight that had struck an overhead power line on approach to a field. This was before the AAIB had its own drone, but a drone operated by the police obtained a good image (Figure 7) from the probable final approach path; this revealed that the cable (now repaired) was very difficult to see against the background of the field. When looking up at the cable from the ground, it was more easily visible against the sky.

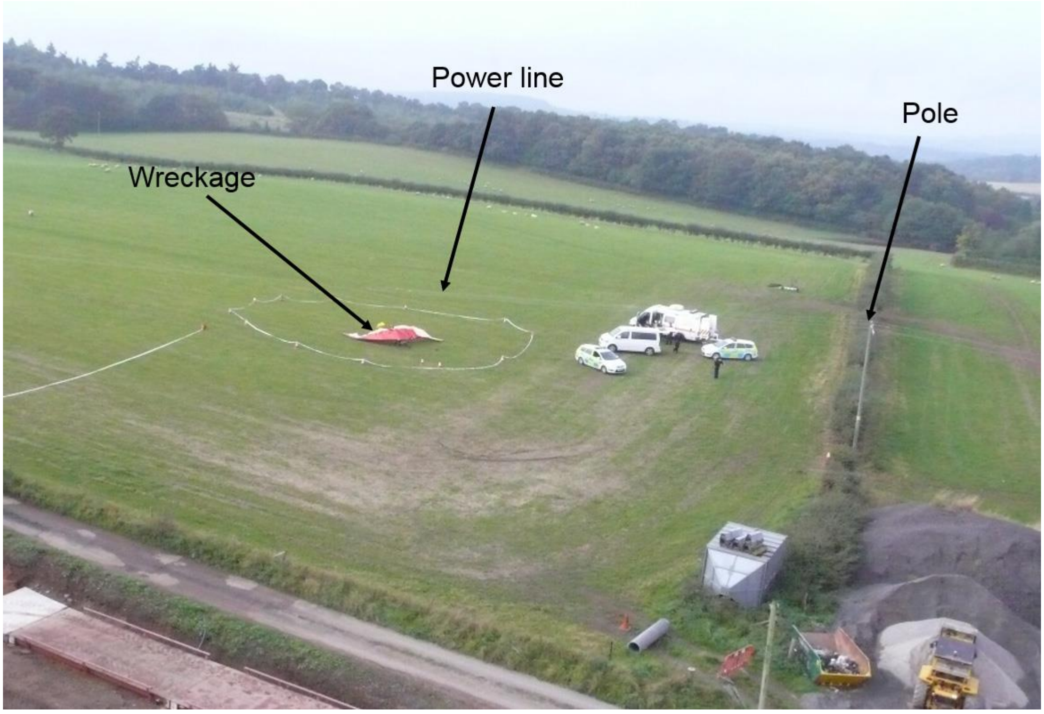


Figure 7

Approximate pilot's eye view of power lines on approach, before the aircraft struck the power line (image from a police drone)

Types of photogrammetry software and how they work

There are many different types of photogrammetry software on the market[2]. The ones that appear to be popular with some drone operators are Pix4Dmapper, Dronedeploy and Agisoft Photoscan. Dronedeploy requires all images to be uploaded to the software company's server for processing which we considered to be inappropriate for sensitive accident site imagery. Pix4Dmapper and Photoscan can perform all the image processing on your PC. When I compared these two, Pix4Dmapper appeared to be more directly tailored to processing drone images than Photoscan, and it also offered a free mobile/tablet app called Pix4Dcapture (used to control the drone) which worked with the software. I also knew someone who had tested Pix4Dmapper with drone images and had obtained good results. So I downloaded the free version called Pix4Dmapper Discovery and my initial results from a few trials were promising so we decided to buy the full version called Pix4Dmapper Pro. A lifetime license is about £6,000 but less expensive one-month and one-year licenses are also available[3]. All photogrammetry software uses the same basic principles, but this paper is based on my understanding of how Pix4Dmapper works (here-on just referred to as Pix4D).

Basic principles of photogrammetry software

Our brains perceive depth by comparing the images that our eyes see. If you look at an object and alternatively close each eye, the object will seem to shift left and right. An object that is closer, will seem to shift more than an object that is farther away. This is stereoscopic vision, and the core concept behind creating the illusion of 3D objects and space from 2D images. Your brain can use this information to subconsciously calculate and tell you how far away an object is. In a similar way,

[2] See https://en.wikipedia.org/wiki/Comparison_of_photogrammetry_software for a long list.
[3] For up-to-date prices and license options see https://mapper.pix4d.com/store/

photogrammetry is a photography technique using software to determine the position and shape of an object by comparing two or more photographs. The science of photogrammetry has been around for over 100 years, but it is only more recently with the advent of powerful PCs and high resolution digital cameras that it has become possible to easily generate 3D models from still images.

How Pix4Dmapper works

Pix4D uses the principles of photogrammetry to convert images into a 3D point-cloud, a 3D digital surface model and an orthomosaic. An orthomosaic is an image that is composed of multiple overhead images and is corrected for perspective and scale, which means that it has the same lack of distortion as a map. The software starts by identifying keypoints in a series of overlapping images. A keypoint is a point of interest, like the corner of a vehicle, that Pix4D can identify in multiple images. Knowing the camera position, orientation and camera properties like focal length, it then projects a line from the camera through a keypoint (Figure 8). It then repeats this for the next image, resulting in a triangulated position of that keypoint in 3D space, which is used to create a point in the 3D point cloud. Ideally you want to take sufficient overlapping images so that a single keypoint can be identified in 4 or 5 different images. In a typical 14 megapixel image Pix4D can identify about 60,000 keypoints. And it will typically find 6,000 matched pairs of keypoints per pair of images. By analysing so many keypoints the accuracy of the project is improved. It also enables the software to back triangulate the camera position and camera properties. It will correct the GPS position of the camera and will also correct the focal length if necessary. The software can even process images that aren't geo-tagged. Without geo-tags it can still generate a 3D point cloud and orthomosaic, but it will not have the correct scale; however, scale can be added by entering known distances between points in the 3D cloud.

Traditional photogrammetry has always relied upon a very precisely known camera position, orientation and optical properties. The technique employed by Pix4D, to analyse multiple keypoints and correct for errors in camera position, orientation and optical properties, is known as modern photogrammetry. It is this technique that enables drones to be used as the camera platform and for low-cost cameras to be used on the drone.

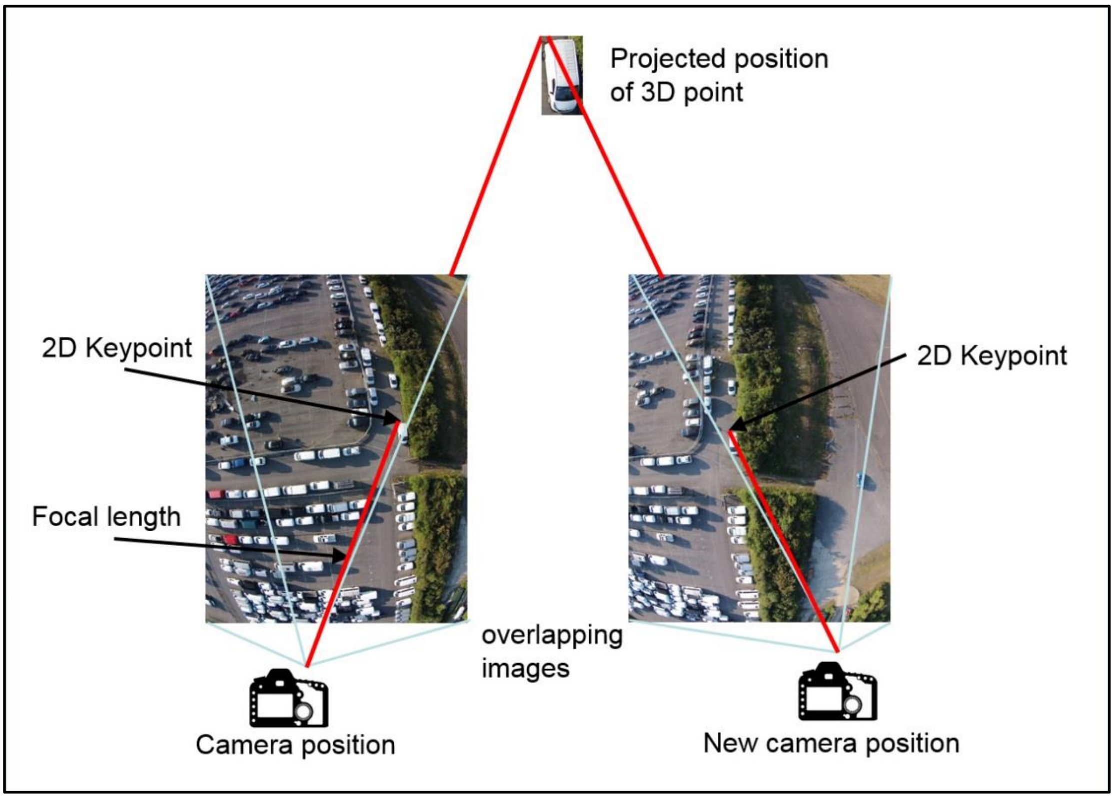


Figure 8
How photogrammetry software calculates the position of a 3D object by identifying common keypoints between overlapping images

How best to acquire images from your drone to use with Pix4D

To enable Pix4D to generate a high quality and accurate orthomosaic (such as the one in Figure 11) you need to acquire a series of overlapping images with the drone camera orientated 90° down, ie pointing straight at the ground; these are called nadir images. The camera needs to have gyroscopic stabilisation to maintain the 90° downwards tilt. Pix4D recommends a minimum of 75% overlap between images. To make it easy to do this Pix4D have created an app called Pix4D capture (which runs on both iOS and Android) that controls the drone. It works with the Phantom series of drones from the 2V+ onwards, the Inspire and some other drones. When you open the app in your location it will download an aerial image (assuming you have an internet connection) and you can draw a box on the image to highlight the area you want mapped. You then select the percentage of image overlap you want and the app will calculate the grid pattern it needs to fly and how frequently it needs to take a still. A screenshot of this grid is shown in Figure 9.

Figure 9

Screenshot of Pix4Dcapture app showing box and calculated grid pattern

The app also contains options to set the speed of the drone. A faster speed will allow you to cover an area more quickly which is useful for large areas that need to be scanned; however, a slower speed will result in higher quality images and a more accurate project. There is also the option called 'SAFE' which causes the drone to stop before taking each image. This results in the best quality images but takes longer and may exceed the battery life for the desired grid.

The most important setting in the app is the flight height. If you choose a high height the drone doesn't need to fly as many legs to achieve the same percentage overlap as flying at a low height, so the area is scanned quicker. This is because at a high height each image contains a higher percentage of the desired area than images from a low height. However, images taken from a higher height will usually result in a less accurate project than images from a low height. What we have found works well in practice is scanning the entire accident site from a height of 50 m or 75 m, and then carrying out a second scan of the main wreckage area from a height of 15 to 30 m. If you're just looking for a general overview image, fly high. If you're looking to generate an accurate 3D point cloud and highly detailed images, fly low.

There are many variables that affect accuracy but one of them is Ground Sampling Distance (GSD). GSD is the distance between two consecutive pixel centres measured on the ground. For example, in an image with a 1 cm/pixel GSD, adjacent pixels image locations are 1 cm apart on the ground. The higher the GSD, the lower the spatial resolution of the image with fewer visible details. The GSD you can expect can be calculated based on camera height, focal length, sensor size and image resolution. The equations can be found online and I've used an online calculator[4] to determine height vs GSD values for the FC200 camera on the P2V+ drone (Table 1). This camera has a focal length of 5 mm, a sensor width of 6.17 mm, and a resolution of 4384 x 3288 pixels. Table 1 also

[4] You can download a tool to calculate GSD from https://support.pix4d.com/hc/en-us/articles/202560249-TOOLS-GSD-Calculator#gsc.tab=0

shows the ground distance width of each image and the distance you would need to allow between images to ensure a 75% overlap. At a very low flight height of 10 m you would need to take an image every 3.1 m.

Flight height (m)	GSD (cm/pixel)	Image width on ground (m)	Distance between images for 75% overlap (m)
10	0.28	12.3	3.1
20	0.56	24.7	6.2
30	0.84	37.0	9.3
40	1.13	49.4	12.3
50	1.41	61.7	15.4
60	1.69	74.0	18.5
70	1.97	86.4	21.6
80	2.25	98.7	24.7

Table 1

GSD and distance parameters as a function of flight height for the FC200 camera on the Phantom 2 Vision Plus

As an example, the red dots in Figure 10 show the position of each of the images that were taken from a height of 50 m to ensure at least a 75% overlap.

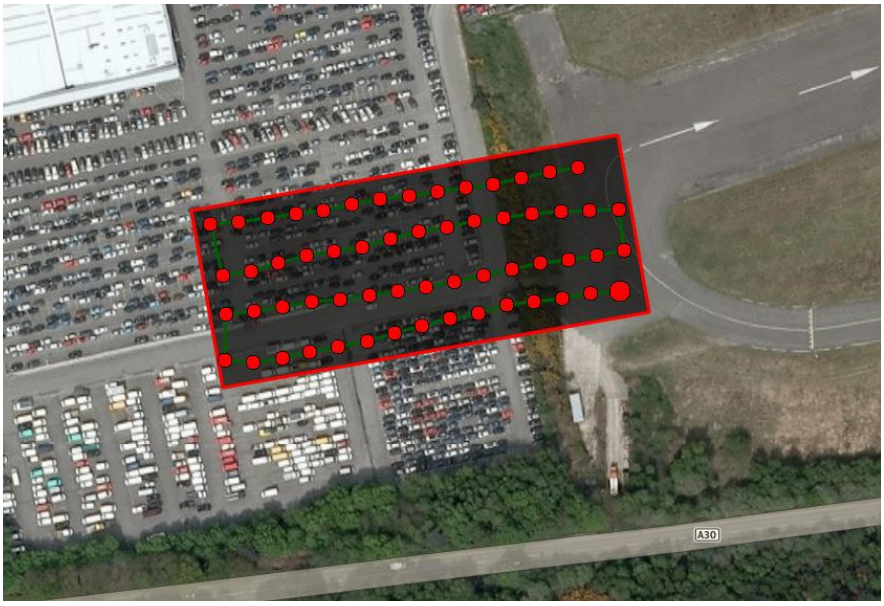


Figure 10

The red dots show the location of each of the 59 images taken automatically by the P2V+ after being programmed to fly at 50 m with the grid from Figure 9

The total flight time, from takeoff to landing, to capture the 59 images in Figure 10 was 9 minutes. The Pix4D processing time for these 59 images was about 1.5 hours using a basic laptop and the resulting orthomosaic is shown in Figure 11. Processing times can be reduced by using a PC with lots of RAM[5] and a high-end graphics card. The original orthomosaic was 'north up', but Figure 11 has been rotated to fit the horizontal.

Figure 11

Pix4D orthomosaic generated from 59 overlapping images taken with a P2V+ from a height of 50 m (a digitally zoomed-in section of this orthomosaic is shown in the lower right corner)

3D point cloud, mesh and Digital Surface Models

Prior to generating the orthomosaic Pix4D generates a 3D point cloud. The point cloud generated by the 59 images previously discussed is shown in Figure 12. The point cloud can be edited to remove any spurious points. The point cloud looks quite pixelated, so there is an option in Pix4D to view a 3D mesh instead. The 3D mesh is a 3D model where all the dots of the point cloud are connected in order to create a surface (Figure 13). The mesh can contain artefacts, especially around the edges of the project where there will have been less image overlap. The mesh is useful to show people what the accident site looked like and it can be easily rotated and viewed from any angle; however, it should not be taken to be the visual truth and it is not a substitute for analysing the underlying images that created it.

[5] Pix4D recommend at least 8 GB of RAM and a graphics card with at least 2 GB of RAM

Figure 12
3D point cloud created from the 59 overlapping overhead images previously discussed

Figure 13
3D mesh created from the 59 overlapping overhead images previously discussed

The quality of the 3D point cloud and mesh can be improved by taking oblique images. An oblique image, as opposed to a nadir image, is an image that is taken from any angle other than 90° down. By taking images from an angle of 45° you can capture more detail from the sides of objects and this improves the quality of the 3D model. For the best results you want to fly in a circle around the main wreckage while keeping the camera pointing directly at the wreckage. The software that controls the Phantom 3, 4 and Inspire allows you to programme the drone to fly automatically around a pre-set point at a pre-set distance, while automatically rotating the camera to keep it on the point. Some manual slaving is usually required to keep the camera precisely pointed in the middle. There are then two ways of taking the images; either manually pressing the shutter button every 1 to 2 seconds (you want to capture at least 30 images in a circle, which is one image ever 12°); or set the video to record in 4k resolution. A 4k video effectively provides you with a continuous series of 8 megapixel images and Pix4D can automatically extract these images from the video (you just tell it how frequently to grab a frame). For the best results it is worth flying two circles at two different heights. These images are then processed in Pix4D using the '3D models' setting. An example of a 3D model obtained from a 7-minute oblique aerial video is shown in Figure 14.

Figure 14

3D mesh created from oblique video from P2V+ while flying two circles at two different heights around the main wreckage

The final product of Pix4D is the Digital Surface Model (DSM) although I have found limited use for it so far. An example DSM generated using the 59 overlapping overhead images previously discussed is at Figure 15. The colours represent the different heights. The hedge-row and individual vehicles in the car park can be easily identified. Given that the average car height is about 1.5 m it is clear that this project has been able to resolve height differences of less than 1 m. The absolute height accuracy, based on the colour coded scale, is in error by about 10 m (the actual car park elevation is 97 m amsl). This is due to the inaccuracy of the drone GPS, but this can be manually adjusted for in the software if necessary. The relative height accuracy in this project is about 20 to 30 cm when measuring car heights.

Pix4D can also generate a .kml and a series of tiles so that the orthomosaic can be viewed in Google Earth as a geo-referenced map. How well it overlays in Google Earth is dependent upon the accuracy of the drone GPS, but manual corrections can be applied. The orthomosaic can also be viewed as an overlay in Google Maps and saved as a GeoTIFF[6] file for viewing and editing in Geographic Information System (GIS) software.

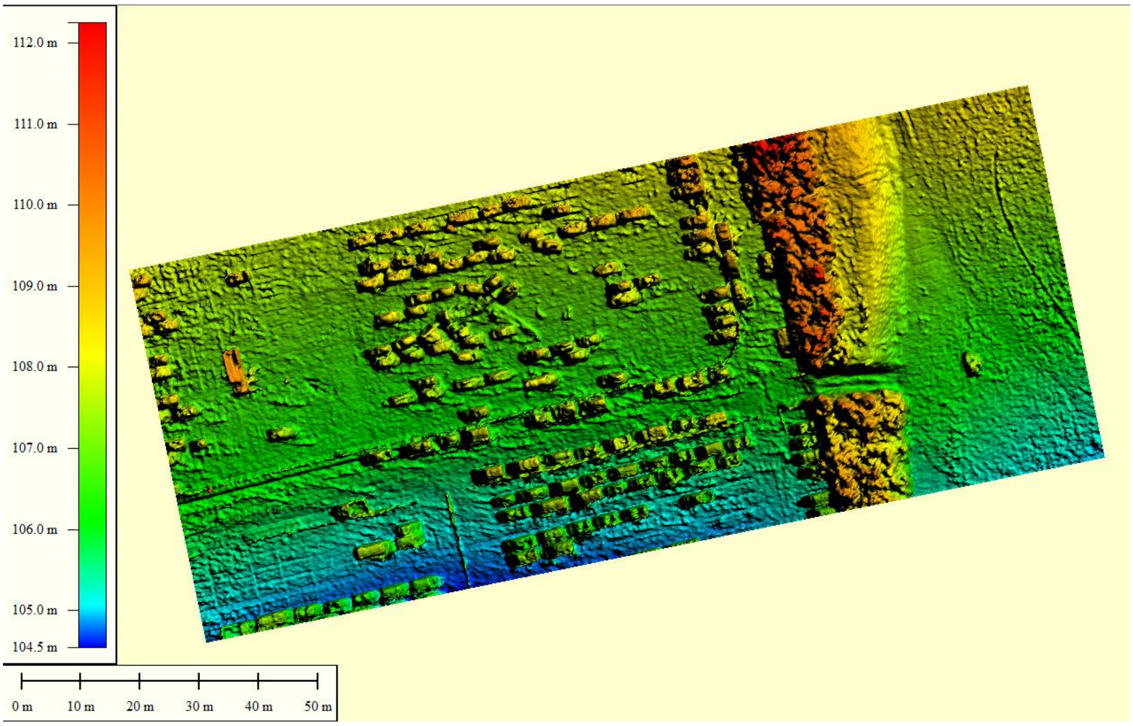


Figure 15

Digital Surface Model (DSM) generated by Pix4D using the 59 overlapping overhead images previously discussed

Measurement accuracy

According to Pix4D if the image resolution is high and the images are of good quality (not blurred and neither over under-exposed), then a linear measurement in the point cloud should have a relative accuracy of about 1 to 2 GSD horizontally. So from a flight height of 40 m a relative accuracy (between points in the images) of 1 to 2 cm should be achievable. Absolute accuracy relative to a global coordinate system could, however, be off by a few metres due to the inaccuracy of GPS. However, if you have access to a kinematic GPS surveying system and you survey a few points that are visible in the aerial images, these can be imported into Pix4D as 'Ground Control Points' (GCPs) and can increase the global position accuracy to within 1 to 2 GSD.

The first time I used Pix4D at an accident site was to process the scene in Figure 11. We had set a 3 m long tape alongside the wreckage as a distance reference. When I measured this distance in the point cloud by selecting the ends of the tape (Figure 16) the resulting distance was 3.01 m. I then measured the length of the right aileron and it was also accurate to within 1 cm. However, at a subsequent accident site we were not able to achieve the same level of accuracy. There are a number of factors which affect measurement accuracy and these include:

- Image resolution, at least 10 megapixels is recommended

[6] GeoTIFF is a public domain metadata standard which allows geo-referencing information to be embedded within a TIFF image file.

- Image quality in terms of focus and exposure
- Flight height, this affects GSD and image detail
- Flight speed, slower is better
- Wind speed, a strong wind can affect the stability of the drone and camera
- Percentage image overlap, at least 75% is recommended
- Pix4D processing settings[7]
- The type of terrain being mapped

The type of terrain being mapped is a significant factor. For example, reflective surfaces like water cannot be processed. Urban areas with lots of detail and contrast will process better than a uniform green field. A sandy desert with no distinguishing keypoints would probably not process at all. Any movement in the scene can affect the accuracy as well, so a strong wind blowing tree branches or crops could affect the results.

Part of the reason we probably got high accuracy at the accident site in Figure 11 was because this was effectively an urban environment with high detail and high contrast. Most of the light aircraft accident sites we attend are in fields, so we conducted a trial by setting out some pieces of wreckage in a large field (Figure 18). We placed six bullseyes (Figure 19) in random positions around the main wreckage so that we had points that could be precisely identified in the point cloud. We measured the distances between these bullseyes with a tape measure to the nearest centimetre. We also placed two 3 m long tape measures, orientated at right angles, near the aircraft fuselage. We then used the Inspire Pro and the pix4D capture app to fly over a large 105x98 m area at a height of 40 m and then a smaller 54x38 m area, centred over the fuselage, at a height of 15 m. We used the maximum overlap setting of 90% and 'safe' mode which meant that the Inspire stopped to take each image. The wind was about 8 to 10 kt. The resulting orthomosaics from heights of 15 m and 40 m are shown in Figures 17 and 18 respectively. The GSD from 40 m was 1.22cm/pixel and the GSD from 15m was 0.47 cm/pixel. The distances between the numbered bullseyes, 1 to 6, are shown in Table 2 together with the Pix4D measurements. The largest error was 8 cm and counter-intuitively, the errors were slightly less from a height of 40 m than 15 m. In terms of percentages the errors were all less than 1% which is acceptable for most of the measurements we are likely to be interested in at an accident site, ie distances between ground marks, distances from the first ground mark to the main wreckage.

I was able to improve the accuracy further by adding a scale constraint. After telling the software that the distance between points 1 and 2 was 13.48 m and selecting 'reoptimise', the resulting distances between the other points were all within 1 cm, as were the lengths of the 3 m tapes.

[7] There are numerous processing settings which can affect the results which are beyond the scope of this paper. Pix4D processing settings are explained in this link https://support.pix4d.com/hc/en-us/articles/202557759-Menu-Process-Processing-Options-1-Initial-Processing-General#gsc.tab=0

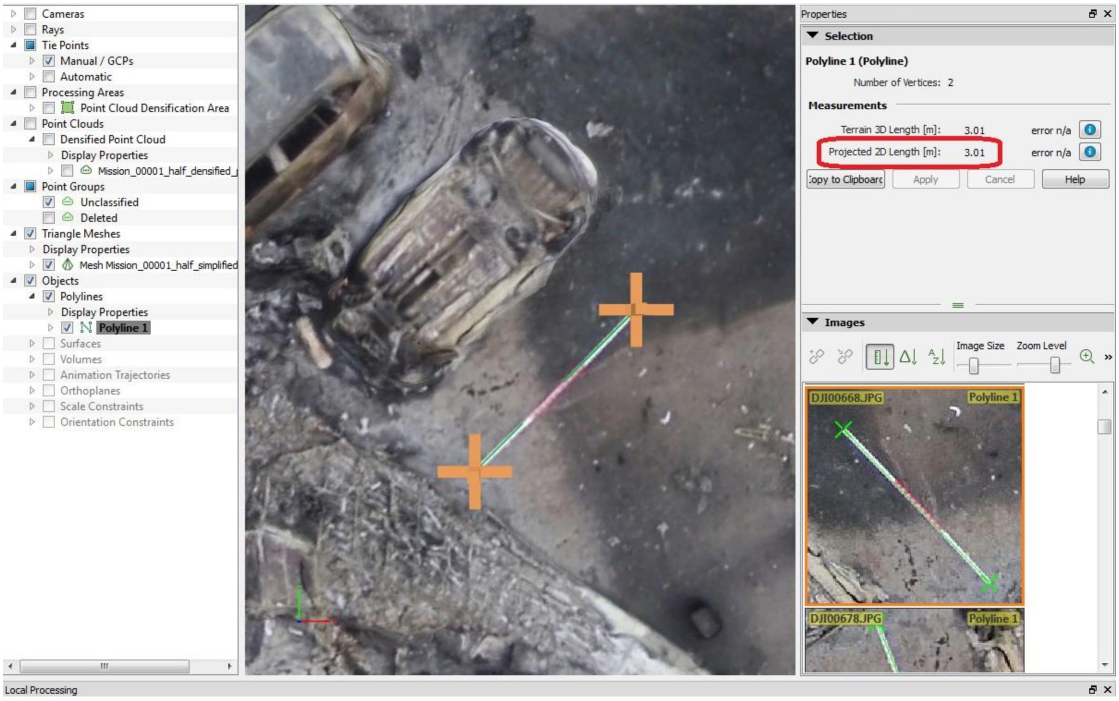


Figure 16

Example Pix4D accuracy over a short distance (project using the 59 images previously discussed). The 3 m ruler placed near the wreckage was measured to be 3.01 m in Pix4D.

Distance	Tape Measurement (m)	15 m height (m)	15 m % diff to tape	40 m height (m)	40 m % diff to tape
1-2	13.48	13.40	0.6%	13.44	0.3%
2-3	13.34	13.28	0.4%	13.30	0.3%
3-4	9.91	9.85	0.6%	9.87	0.4%
4-5	9.12	9.06	0.7%	9.09	0.3%
5-6	11.20	11.15	0.4%	11.16	0.4%
6-1	15.43	15.35	0.5%	15.41	0.1%
3m lat	3.00	2.97	1.0%	2.98	0.7%
3m long	3.00	2.97	1.0%	2.99	0.3%

Table 2

Comparison of tape measurements with Pix4D measurements from projects using nadir images from 15 m and 40 m heights (images taken with Inspire Pro); 3m lat and 3m long refer to the two 3m tape measures, one placed laterally and the other longitudinally relative to the fuselage

Figure 17
Orthomosaic from 71 images at height of 15 m using Inspire Pro (inset shows zoomed-in detail) – the area covered in the image is 54 x 38 m

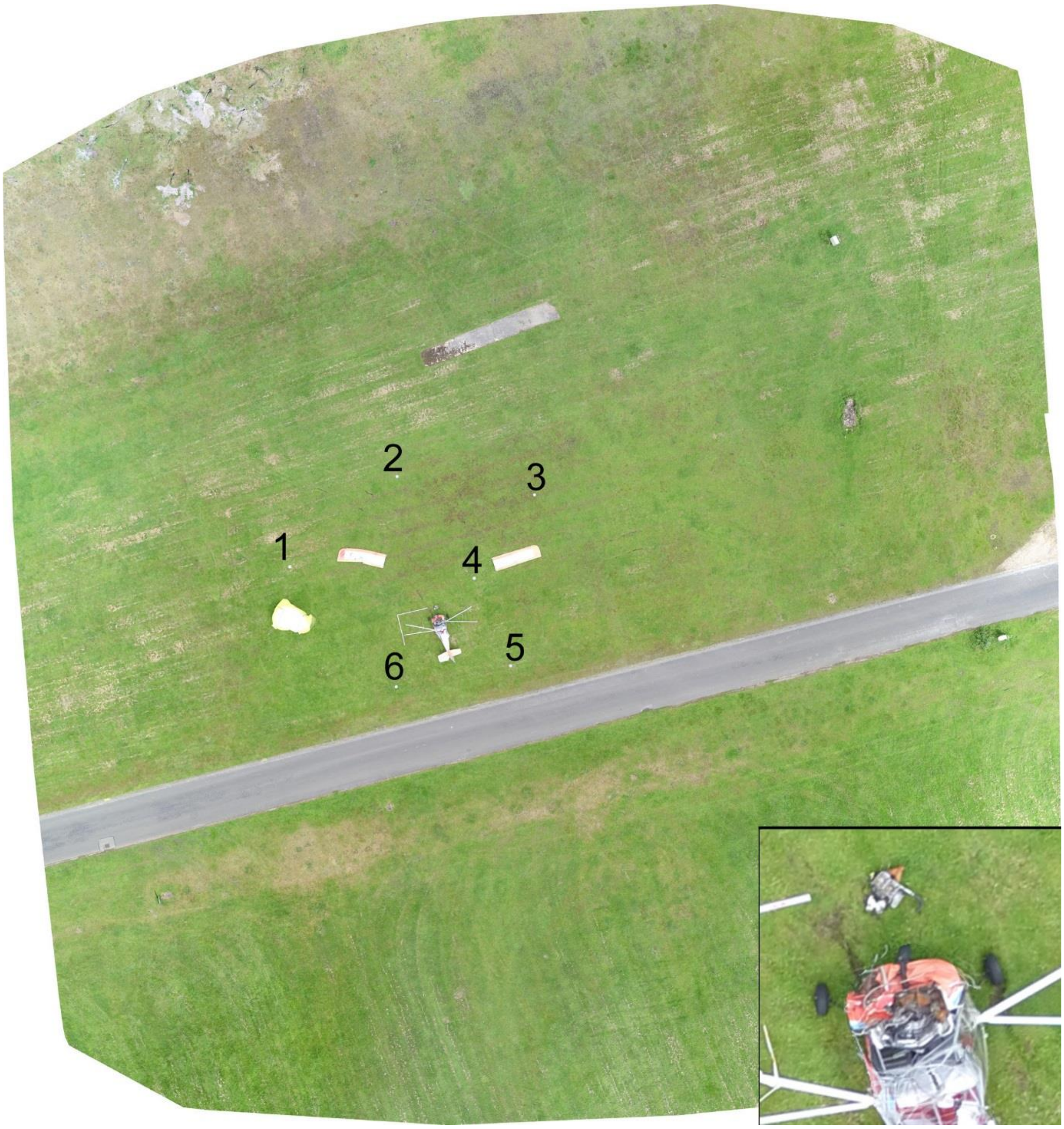


Figure 18

Orthomosaic from 75 images at height of 40 m using Inspire Pro (inset shows zoomed-in detail) – the area covered in the image is 105 x 98 m

Figure 19
Image from a height of 15 m of one of the bullseyes (28 cm diameter) laid around the wreckage at the numbered points in Figures 18 and 19

Pix4D and RCMP accuracy trial

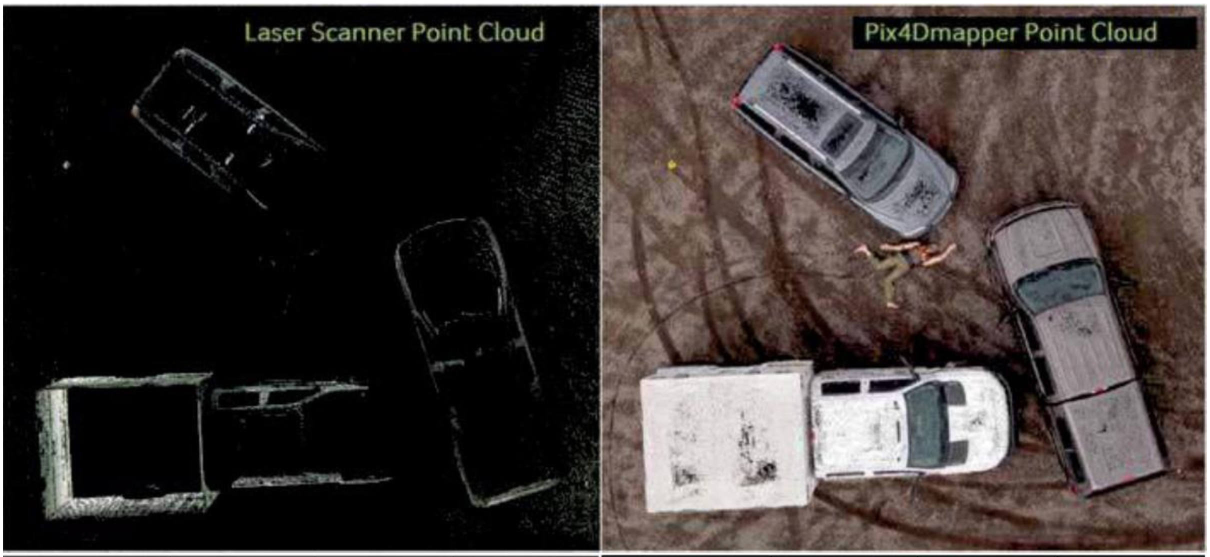
Pix4D carried out a joint project with the Royal Canadian Mounted Police (RCMP) and published a paper on '*UAV Based Collision and Crime Scene Investigation*'[8] where they set up a small accident scene involving three vehicles and a dummy lying on the ground. They used kinematic GPS survey equipment to locate a number of points and imported these positions into Pix4D to improve the accuracy. They also took tape measurements between the points and compared these to the output from Pix4D. Their results are shown in Table 3 which revealed accuracies of between 1 and 3 cm compared to the tape measurements, and accuracies of 1 cm when compared to the surveyed distances.

	#1 ~ #2	#3 ~ #4	#5 ~ #6	#7 ~ #8
Marker Corners (GCPs)	5.00 meters	9.99 meters	7.50 meters	12.32 meters
Tape Measurement	5.00 meters	10.00 meters	7.50 meters	12.34 meters
UAV+Pix4Dmapper	5.00 meters	9.98 meters	7.49 meters	12.31 meters

Table 3
Pix4D accuracy figures from an RCMP trial of a small accident scene using Ground Control Points surveyed by kinematic GPS equipment

They also compared the Pix4D measurements to the results obtained from laser scanning equipment, which are shown in Figure 20.

[8] This paper can be downloaded from https://support.pix4d.com/hc/en-us/articles/203270875-Scientific-White-Paper-UAV-Collision-and-Crime-Scene-Investigation#gsc.tab=0



	Truck Height	Truck Length	Truck Width
RCMP Truck	1.70 meters	2.87 meters	2.43 meters
Laser Scanner	1.67 meters	2.87 meters	2.42 meters

	Truck Height	Truck Length	Truck Width
RCMP Truck	1.70 meters	2.87 meters	2.43 meters
UAV+Pix4Dmapper	1.70 meters	2.87 meters	2.43 meters

Figure 20

Results from RCMP trial comparing the point cloud and accuracy obtained with Pix4D compared to laser scanning equipment. (copyright Pix4D)

Projects using ground imagery

Pix4D can also be used to process images taken from the ground. Figure 21 shows the 3D model (mesh) of a propeller blade that it generated using 35 images taken with my Canon Powershot G11 camera. I walked around the propeller blade twice, taking an image about every 20°. On the first revolution I took the images by crouching down so that the camera was level with the middle of the blade, and on the second revolution I took images standing up with the camera tilted downwards about 45°. I have had less success using this method on an aircraft wreckage in a field. Ideally you want to minimise any distant background or sky in the images, otherwise Pix4D will select most of the keypoints from the background and you will get a model of the background with limited detail of the object of interest. This problem is avoided with aerial images because the background is the ground which is very close to the object of interest. To get better results of a large object using ground-based images it is worth investing in a long selfie stick. DJI sell a gyro-stabilised camera called the Osmo that can be mounted on the end of a selfie-stick (82 cm long) and controlled by a smartphone. This allows you to take images with the camera angled downwards on to the object, minimising the amount of sky, and maximising the amount of ground in the background. The results from using this method are shown in Figure 22. Because the Osmo camera can take 4k video I used video instead of stills and it took just 3 minutes to walk around the wreckage twice.

Once a project has been created using ground-based imagery or oblique aerial imagery, these projects can be merged with one taken with aerial nadir imagery, so that a detailed 3D model can be combined with accurate distance measurements. The merging process involves manually identifying at least 4 or 5 common points, called manual tie points, and the software uses these to create a combined project.

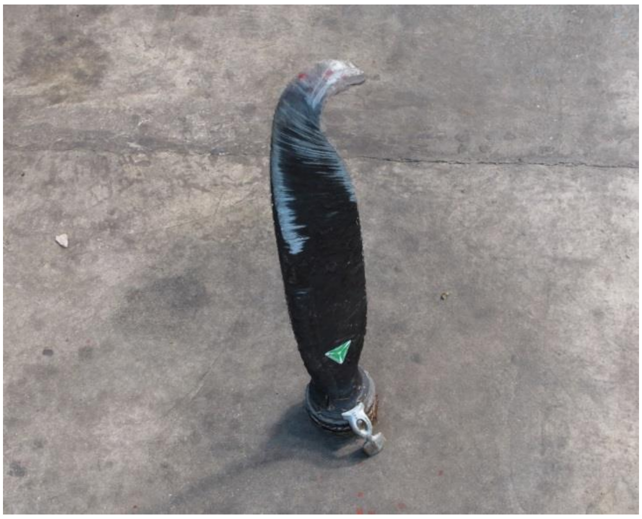


Figure 21
3D model (mesh) of a propeller blade – processed using 35 still images taken at ground level using a Canon Powershot G11 camera (10 megapixel setting)

Figure 22
3D point cloud created using ground-based video from a DJI Osmo X3 camera mounted on a selfie-stick

Benefits of photogrammetry software for processing accident site imagery

Taking aerial images of an accident site and processing them with photogrammetry software has a number of benefits. The 3D model is very useful for briefing people who have not attended the accident site. You can manually zoom in and out and rotate the model to show all the ground marks and wreckage distribution. This can make it easier for people to visualise the site compared to flicking through a number of still images. You can also use Pix4D to create an animated video of the 3D model which can then be sent to people to view who do not have the Pix4D software. If some time has passed between attending the accident site and writing the report then viewing the 3D model can serve as a useful refresher. However, there are limits to the 3D model. It can contain artefacts and it is not as detailed as the raw images used to create it, so it should not be seen as a replacement of the raw images.

I have found the orthomosaic image of an accident site to be even more useful than the 3D model. It effectively serves as a very detailed wreckage plot and I find myself spending less time trying to draw a sketch of the site. I will note down any objects that are unlikely to be seen in the aerial images, but for the most part I can rely on the orthomosaic for documenting the positions of the major parts of wreckage and their relative positions to ground marks. I have always found it difficult to draw a wreckage plot to scale, so the orthomosaic does that for me. We keep a laptop with our drones and it is best to process the images onsite to check the quality of the orthomosaic, before making decisions that rely upon having it.

It is very important to make a few manual measurements, using a tape measure or laser distance meter, between points that will be identifiable in the images. This enables you to check the accuracy of the model and orthomosaic, and these distances can also be entered into Pix4D using the 'Scale' option. The 'Scale' option will re-optimise the project using your known distances to help reduce any inaccuracies.

When you have a project with accurate scale you can spend less time taking manual measurements onsite and you will obtain more accurate position information than from using a hand-held GPS. And it's very useful having an orthomosaic if, when you get back to the office, you find out that you forgot to measure a particular distance.

The Pix4D model is also useful for obtaining height measurements that are difficult to obtain in the field, such as the heights of trees. Height measurements are not as accurate in Pix4D as horizontal measurements but they are useful for providing estimates. I intend to carry out a detailed comparison of height measurement accuracy at a future date.

The orthomosaic is also a useful tool to search for missing wreckage, particularly for large accident sites, and it can be reviewed in slow time back in the hotel or office.

An orthomosaic is effectively a map and can also be used for planning the recovery of wreckage at large accident sites. In August 2015 we used our P2V+ at a large 270 x 50 m accident site covering a road and woods where an ex-military Hunter aircraft had crashed during a display. I generated an orthomosaic of the site on day 3 which was printed out and used by the AAIB and police to draw grids and plan which areas were going to be cleared first. At this site the police also used a laser scanner. The laser scanner needed to be set up on a tripod at different positions throughout the site and it took more than two hours for the whole site to be mapped in this way. In comparison, the P2V+ flight, that generated the 100 images used to create the Pix4D orthomosaic, took just 10 minutes. The main benefit of laser scanners is that they provide reliable and accurate measurements, but they are expensive, time consuming to use, and sometimes it can be difficult to find appropriate locations to set up the scanners so some objects can be missed.

Conclusions

The AAIB has found drones to be a very useful tool at accident sites. They can be used to take images and video to survey the accident site, and to perform final flight path reconstruction/visualisations. The live video from a drone can be used to search for wreckage, conduct a site safety assessment and oversee operations on site. Drones can also be used to estimate tree and other object heights. A drone costs significantly less to operate than a manned aircraft and it can be flown in low visibility and low cloud conditions that would prevent an aeroplane or helicopter being operated. Drones can be deployed immediately on arrival at site and therefore are able to document the site before it becomes disturbed by investigation and recovery activity. A drone can be easily re-launched to take additional footage, and the investigator has full control over the images and video taken. A drone can be flown closely to trees and wreckage to obtain close-up images without disturbing them with rotor downwash.

A drone can be easily programmed to take a series of geo-tagged and overlapping overhead shots for photogrammetry purposes. Photogrammetry software like Pix4D can then be used to create geo-referenced maps, orthomosaic images, and 3D models of an accident site. The 3D model is very useful for briefing people who have not attended the accident site and for 're-visiting' the scene when writing the report. The software enables measurements of a site to be taken that can be to 1 cm accuracy, which means that less time is spent on site making manual measurements and drawing sketches.

The combination of drone imagery and photogrammetry software provides a very useful new tool and link in accident site documentation and analysis, and at a much lower cost than hiring a commercial helicopter or using laser scanning equipment.