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Allison, Matthew; Hall, Jonathan; Jones, Stephen M

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Authors:

Allison, M.S., Hall, J.R., Jones, S.M., Department of Geology, University of Birmingham, UK

Corresponding author: m.allison@bham.ac.uk

Twitter:

@Matt_S_Allison

@jhgeol

A Practical Guide to Virtual Outcrop Photogrammetry in Earth Science

Matthew S. Allison[a,*], Jonathan R. Hall[a], Stephen M. Jones[a]

[a]University of Birmingham, B15 2TT, UK

Abstract

In 2021, a photogrammetric model of a 7 km coastal cliff section of the Tjörnes Peninsula, northeastern Iceland was constructed to provide a "virtual geological outcrop" at a spatial resolution of approximately 5 cm or less. Field expedition planning and post-expedition processing were somewhat hampered by a lack of freely accessible guiding resources. This document presents a first-hand case study of the complete project workflow, including expedition planning, field data acquisition, and data processing within Agisoft Metashape software to create an interactive "Structure from Motion" photogrammetric model for uploading to the V3Geo cloud-based platform. Drone-based photogrammetry is a burgeoning tool, and this account is intended to allow safer, more effective and more efficient use of the technology in creating virtual outcrops for use in Earth science teaching and research.

1. Background

The history of photogrammetry dates back to the mid 19th Century (Polidori, 2020). More recently, a photogrammetric technique termed "Structure from Motion" (SfM) has been developed that allows 3D geometries to be calculated from unordered, overlapping two dimensional (2D) images (Schonberger and Frahm, 2016). SfM is a technique that allows large swaths of land to be

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*Corresponding author
   Email address: m.allison@bham.ac.uk (Matthew S. Allison)

surveyed by drone and the resulting images fed into software to reconstruct the landscape. The term "drone" used herein means a semi-autonomous flying platform with a camera; drones are also commonly termed Remotely Piloted Vehicles (RPVs) or Unmanned/Un-piloted Arial Vehicles (UAVs). Applications of SfM technology based on drone imagery are manyfold and burgeoning. Within the field of Earth Sciences, for example, SfM applications include mapping of geo-hazards (Suh and Choi, 2017; Backes et al., 2019), structural geology (Bemis et al., 2014), glaciology (Westoby et al., 2015) and thermal surveying of an active volcano (Wakeford et al., 2019). As the niche of geological SfM photogrammetry becomes more mainstream, a system of supporting infrastructure has emerged, including the V3Geo provides a browser-based cloud platform for hosting and viewing 3D virtual outcrop models (VOG Group, 2022a).

This paper outlines our experience in producing a 3D "virtual outcrop" SfM model for the V3Geo platform (VOG Group, 2022b) (Fig.1). The over-arching project targeted the Tjörnes Beds of northeastern Iceland, a predominantly coastal exposure of Late Neogene sedimentary rocks. The Tjörnes Beds have historical significance, are the thickest sedimentary section in Iceland, contain a
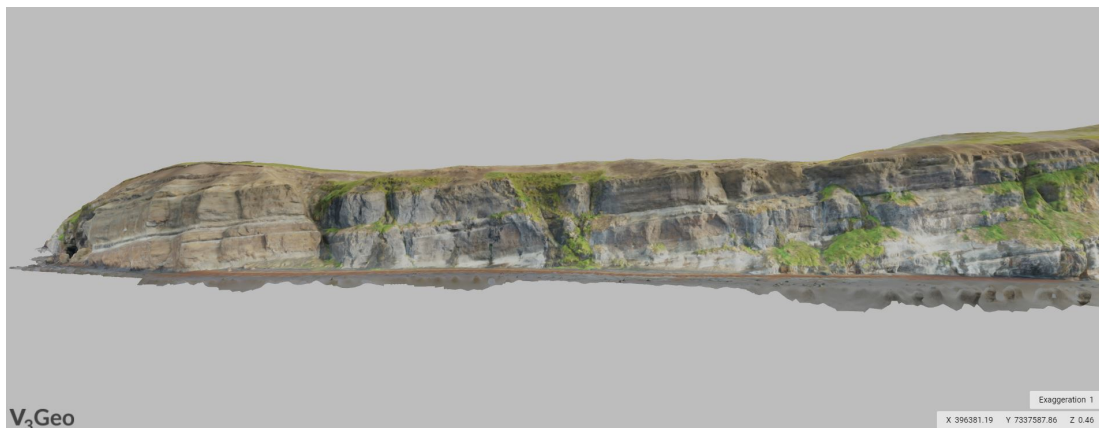

Figure 1: A screenshot of the northern extent of the Tjörnes Beds V3Geo photogrammetric model.

useful palaeoclimate archive, and expose a variety of sedimentological and structural features suitable for teaching (Símonarson and Eiríksson, 2008; Eiríksson et al., 2021). We aimed to capture the entire coastal exposure of c. 7 km length within a single virtual outcrop model for the V3Geo platform with uniform cm-scale visible resolution. However, we were hampered by a lack of freely accessible guiding resources at all stages of planning and executing this project. Therefore, this paper aims to document the complete workflow as a case study in order to aid safer, more effective and more efficient use of the technology in creating virtual outcrops for use in Earth science teaching and research in future. The workflow is divided into three parts. (1) The project planning stage, including drone selection (we used a DJI Mavic Pro 2), safety aspects, and preparation of the required equipment. (2) The data acquisition stage, including detailed account of how the photogrammetric survey was programmed and executed in the field. (3) The data processing stage, including step-by-step instructions for using Agisoft Metashape Professional software to build the model, and for uploading the model to the V3Geo platform.

2. Project Planning

2.1. Choosing the Right Drone

Currently available drones range from small toys to thoroughbred videography equipment. There are three main aspects that should be considered before purchasing a drone for geological photogrammetry work.

1 **Functionality**. Is the camera and gimbal structure of the drone capable of capturing raw data at the required spatial resolution, and does the drone have a suitable built-in GPS?

2 **Practicality**. If the field area is remote then pack size and weight should be a consideration. Bear in mind that supporting accessories (batteries, controllers etc.) will also need porting to and from the site.

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3 *Cost*. Camera equipment costs quickly enter a world of diminishing returns, and drones are no exception. A focus on features relevant to the project will help keep costs to a minimum.

For our project, we focussed on drone products from DJI (Da-Jiang Innovations) Technology Co. Ltd. for several reasons: DJI products are commonly used for aerial photography and videography; a range of drones at varying price points is available; and there is no shortage of general online advice on how to operate these drones (although freely available advice specifically on the generation of large virtual outcrop is lacking). Based on the three categories listed above, we considered two types of DJI drone to be well suited for collecting 3D photogrammetry data for virtual outcrop building: the DJI Mavic series and DJI Phantom series. We chose the Mavic Pro 2 (DJI, 2022) for its light weight, foldable and compact form factor, high-resolution camera, leading mid-range battery performance, and compatibility with DJI's Ground Station Pro application. Although this case study focuses on the Mavic Pro 2, the workflow is more widely applicable. In 2021, DJI accounted for over 50% of the global drone market (DroneXL, 2021) and, in our experience, DJI offer a consistent operator experience across their product range.

The Mavic Pro 2 will attach GPS metadata to every image it takes. The accuracy of this GPS position has been shown to produce SfM models with an absolute positioning error of c. 3 m (Kalacska et al., 2020), which was sufficient for our purpose. The camera provides a 20 MP image from a 1 inch sensor. Unusually for a drone camera, it has aperture control between f/2.8 – f/11, which provides ample flexibility in capturing images of different rock types in different light conditions. The camera is stabilized on a 3-axis gimbal, providing manual tilt control between $-90°$ and $30°$ (from vertically down to $30°$ above the horizontal). The remote controller has a maximum transmission range of 6 km (unobstructed line of sight and no interference) and the drone is rated for flight in up to 38 km/hr winds. The drone has a surprisingly small form factor, making it an good candidate for remote geological fieldwork.

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The workflow described herein was conducted using the equipment and software outlined in Table 1. Costs and product details are provided as an example of the investment necessary to carry out a similar project.

In our experience, battery charging was a significant limiting factor in our project. Carrying nine batteries allowed for a total flight time of c. 3 hours per day. The 3850 mAh batteries take c. 90 minutes to charge, representing 13.5 hours/day of charging for the nine batteries used in our project. By using two charging hubs, we were able to charge 2 batteries simultaneously and reduce the total charge time to an overnight task. In total, the weight of an iPad, drone, controller and nine batteries added c. 4kg to the luggage weight. It is important to consider how to pack your equipment and ensure you can safely commute to the target location.

The iPad enabled use of DJI's Ground Station Pro (GS Pro) software, which

Product	Details	Cost/Unit (£)
Drone	DJI Mavic Pro 2	£1,219
Drone Accessories	DJI Mavic 2 Fly More Kit	£339*
Extra Drone Batteries	DJI Mavic 2 Battery x6	£129*
iPad	iPad Air 4 + Cellular	£709*
High Performance Laptop	Alienware X15 Core i9	£3,349
SD Cards	SanDisk 128GB Micro SD Card x2	£22
Hard Drive	Seagate 1 TB External Hard Drive	£40
Drone Automated Survey Software	DJI Ground Station Pro	Free
Photogrammetry Software	Agisoft Metashape Professional	£2,570*

Table 1: Equipment and software list, prices as of Spring 2022. * Educational discounts/licenses may be available on these products.

allows automated execution of pre-calculated flight plans. These automated surveys generate a substantial amount of images, so high capacity micro-SD cards are required as well as an external hard drive to allow for archiving and backup of the micro-SD card data.

SfM 3D models can be georeferenced by using either the onboard drone GPS or by using Ground Control Points (GCP). The internal GPS on the Mavic Pro 2 has been demonstrated to produce SfM models with an accuracy of c. 3 m (Kalacska et al., 2020). GCPs represent targets placed across a survey area which are used to constrain the georeferencing of the SfM model, resulting in centimetre-level positional accuracy (Agüera-Vega et al., 2017). Considering the large survey area (7 km of coastline) and project time constraints (maximum 3 weeks in the field), it was decided that the accuracy offered by internal GPS would suffice for our project. Capturing the complete sedimentary succession with sub-centimetre-scale features being uniformly visible in the final virtual outcrop model was prioritized over <3 m absolute positional accuracy. Should <3 m accuracy geolocation be required then the use of GCP is advised.

2.3. Safe Operation of a Drone

This workflow in this case study does not guarantee the safe and legal operation of a drone. Varying regulations exist depending on where you are operating your drone and the type of drone in operation. Know the law and ensure you have enough flying experience to safely operate the drone. This document presents a semi-automated workflow for drone-based data collection. The drone operator is ultimately responsible for the machine and any damage it could cause. Whilst modern drones are increasingly reliable, the possibility for them to crash when using more autonomous modes of operation should not be neglected. The operator might need to take manual control of the drone at any moment in an automated flight. Good knowledge of the local area, topography, weather, drone, wildlife, private property, personal ability and law are all necessary to ensure safe operation of a drone. Practise in a safe, controllable environment (ideally with a

more experienced operator) and gain experience in flying your drone in all the modes of operation it provides.

2.4. Pre-Survey Checklist

Before embarking on fieldwork, you should ensure the following:

- **Equipment**   All equipment is flight-ready and the latest updates are installed across all software and hardware.

- **Experience**   All drone operators are familiar with the hardware and software they will be using. Practice flights and training have been undertaken to ensure operators are sufficiently confident to safely execute the planned survey.

- **Regulations**   Operators are aware of the local regulations regarding drone flying within their field area. Any flying license or permits have been obtained prior to flight. Drone exclusion zones have been identified and avoided (e.g. airports).

- **Local Area**   Remote reconnaissance of the local area has been undertaken using online satellite data prior to departure for the field area. Once in the field, in-person reconnaissance prior to the survey commencing is recommended to ensure a familiarity with the local area and any hazards that may present.

3. Field Data Acquisition

3.1. Summary of Workflow

Below is a summarised version of the detailed workflow for capturing and processing of drone based photogrammetry:

- ***Survey Planning***   Identification of the survey target and desired level of detail. Flight plans are to be made using DJI's GS Pro.

- ***Data Collection***   Careful assessment of the survey area needs to be made in person and the flights plans adjusted and executed accordingly.

- ***Data Processing***   Image should be fed through Agisoft Metashape and the resulting model cleaned and exported.

3.2. Photogrammetric Survey Planning

As with any field-based project, available time in the field regulates what is achievable. Once a target area is identified, flight planning can allow for survey times to be estimated. Fig. 2 highlights the performance statistics of the Mavic 2 Pro during data collection. On average, a single battery provided 22.5 minutes of flight time, which is significantly less than the 31 minutes advertised by DJI. Battery performance is affected by the weather. Table 2 highlights the average values of temperature, wind speed and precipitation from a nearby weather station to our field area (Iceland Met Office, 2012). In our experience, 1 hour of flight time required full use of 3 batteries, and in that time it was possible to survey c. 5 hectares.

Our total survey area was subdivided into smaller zones in order to keep the drone close to the operator and within line of sight at all times. These smaller zones were scaled such that GS Pro would estimate survey times of c. 30 minutes for each zone. When conducting large drone surveys, tracking the progress of acquiring data within these smaller zones allows for effective time management and planning in the field.

Data Range	Temperature (^{o}C)	Wind Speed (m/s)	Precipitation (mm)
5 year average	3.3	3.6	66.4
30 year average	3.9	2.4	94.0

Table 2: The last 30 year and 5 year averages from Akureyri weather station for the month of September. These three variables provide key limits on battery performance.

DJI Mavic 2 Pro *Real World Performance*

Flight Data:

Distance: 305 km

Flight Time: 28 hours

Battery Performance:

Photogrammetry:

Survey Area: 140 ha

Survey Rate: 5 ha/hour

Data size: 215 Gb

Images: 17,360

Advertised Battery Life — 31 mins

Real World Battery Life — Max — 25 mins

Average — 22.5 mins

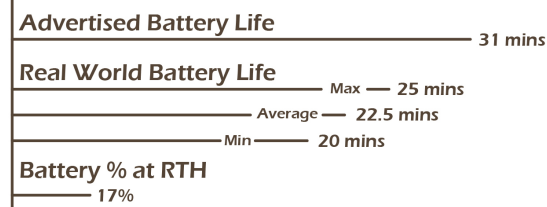Min — 20 mins

Battery % at RTH — 17%

Figure 2: Real world drone performance. Data representative of 60 flights. RTH = Return To Home, an automated process by which the drone returns to its take-off location when on low battery.

It is important to understand the morphology of the survey area to design an efficient photogrammetric survey. All parts of the survey area need imaging in order to contribute to a SfM reconstruction. Thus the orientation and surface expression of an outcrop dictates how the drone needs to be positioned in order to be fully imaged. In this paper three types of exposures and the resulting survey designs are outlined in Fig. 3. The position of the drone camera shall be referenced to the horizontal (0°), where negative and positive camera angles are below and above the horizon respectively. Two possible methods for image acquisition are outlined in this report, termed "area surveys" and "waypoint surveys". An area survey is defined as series of parallel flight paths that occur within an arbitrary bounding polygon (see Fig. 4b: Survey Type — Area). A waypoint survey is defined as a single path along which images are taken (see Fig. 4c: Survey Type — Waypoint).

Type 1 Exposure. The majority of this type of exposure is along a
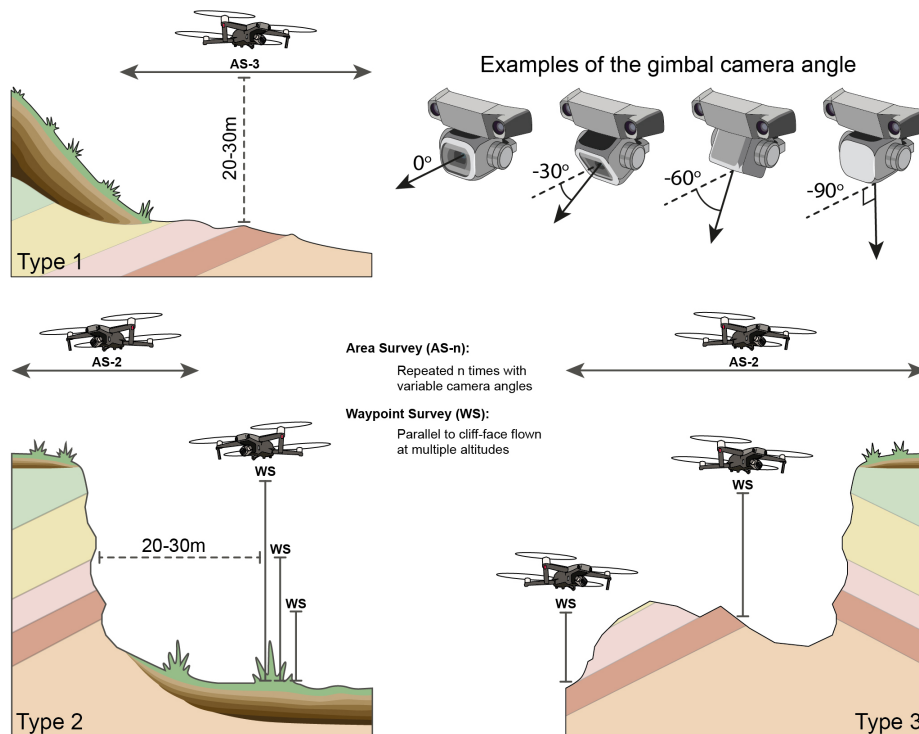
Figure 3: 3 types of outcrop and the proposed survey designs to best capture photogrammetric data. Type 1: Mostly horizontally exposed outcrop. Type 2: Mostly vertically exposed outcrop. Type 3: A mixture of Type's 1 and 2.

horizontal surface, such as a wave-cut platform. This type of exposure can be effectively mapped by repeating an area survey three times, with camera angles of $-90°$, $-60°$ and $-30°$ for the first, second and third surveys respectively (see "Survey Design in GS Pro" for details and Fig. 5a). The three surveys should use the same flight path and capture images at the same positions. The combination of these three surveys records sufficient information for a SfM model.

Type 2 Exposure. The majority of this type of exposure is a vertical surface, such as a cliff face. A waypoint survey should be designed for this type of exposure. Nodes should be established along a line parallel to the cliff-face (e.g. every 15 m). At each node, a series of commands should be executed to capture

multiple images (Fig. 5b). It is recommended to captured 4 images at $-90°$, $-60°$, $-30°$ and $0°$. This waypoint survey should be repeated several times at increasing altitudes to produce a series of parallel lines, stacked vertically a top one another. Ideally the vertical exposure should be imaged by no less than 3 waypoint surveys, so the vertical spacing is a function of the height of the exposure (e.g. a 100 m cliff would result in 3 surveys at 30, 60 and 90 m elevation). An area survey is also recommended, repeated twice with the camera angled at $-90°$ and $-45°$ (the third area survey recommended for Type 1 exposures can be omitted because of the co-located waypoint survey). The area surveys can be quite small as the footprint of a cliff-section is typically quite small. Some areas of the cliff-face might need some manual imaging should any overhanging crags or complex geometry exist. Cliff sections can also develop harsh shadows depending on the lighting conditions and direction of sunlight; see the Camera Settings section for a discussion on how to best manage this.

Type 3 Exposure. The third exposure type exists somewhere between vertical cliffs and horizontal exposure. These types of exposures, typical of most inland outcrops, require a combination of area and waypoint surveys to acquire sufficient imagery for photogrammetric reconstructions. An area survey, repeated twice with the camera positioned at $-90°$ and $-45°$, is recommended followed by a waypoint survey, oriented parallel to the main sloped surface capturing four images at $-90°$, $-60°$, $-30°$ and $0°$ at every node. Should multiple, prominent surfaces exists, several waypoint surveys can be planned to image these exposures in sufficient detail as in Fig.4b.

The survey design outlined in for Type 3 Exposure represents the method used to capture the vast majority of the imagery underlying the V3Geo model of the Tjörnes Beds (VOG Group, 2022b) (1571/17123 images). The target of this model was a 7km stretch of coastal cliffs aligned roughly north-south. The geology crops out near the top of 40-70 m tall cliffs with the base of the cliffs often covered in scree and vegetation. In general, the main target of the survey was imaged from a distance of 20-30 m. This photographic distance resulted in visible centimetre-scale details across the entire section. Areas rich in detail

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or consisting of complex geometry were imaged manually at distance c.10 m. An example of the actual flight paths designed in GS Pro for a portion of the

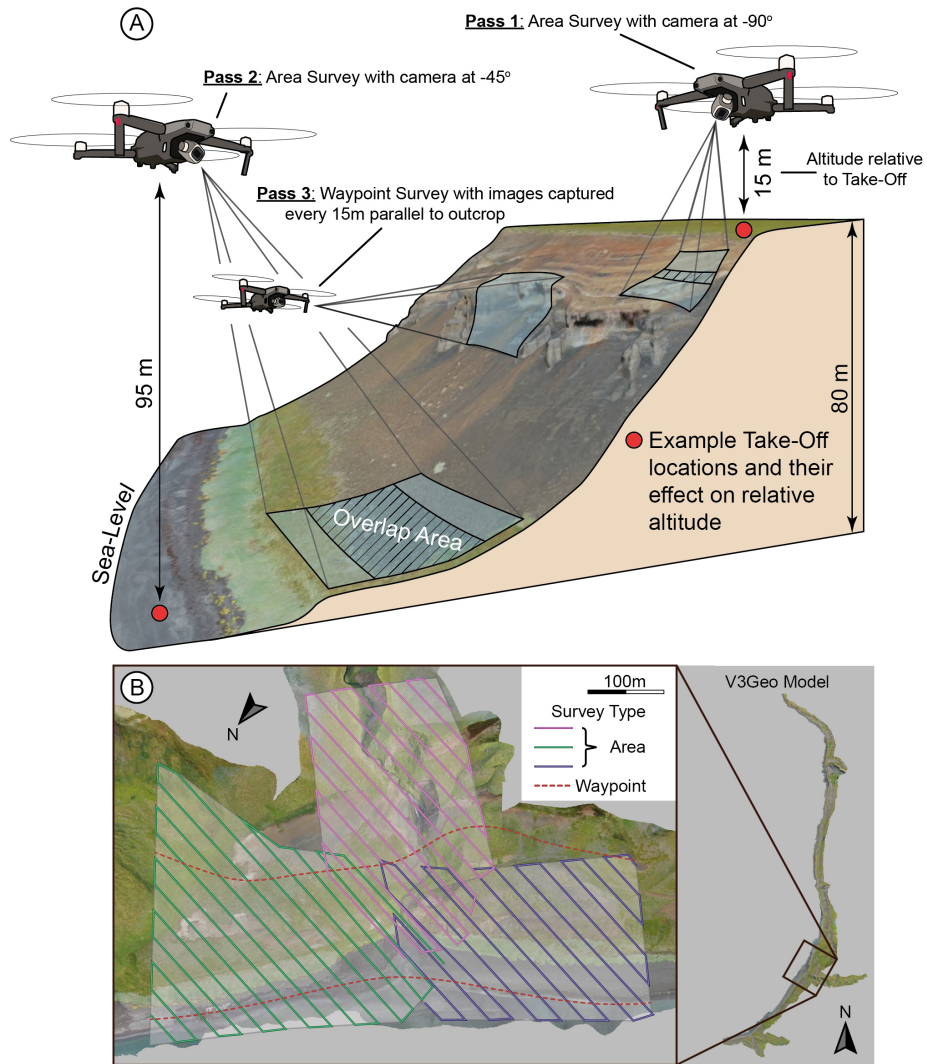Figure 4: (a) Summary of data collection in the field. Highlighted is the variation in both image size and image overlap due to variable topography within the survey area and the dependent nature of relative altitude to the take-off location. (b) An example of the survey design for a portion of the Tjörnes Beds V3Geo model, highlighting overlapping Area Surveys and Waypoint Surveys to target prominent exposures.

Tjörnes Beds survey can be found in Fig.5.

Automated surveys are designed to operate at a fixed altitude, this has the following disadvantages:

1 **Variable Resolution**: Should the topography rise and fall under the survey area, the resulting model fidelity will vary due to the camera being physically closer or further from the land.

2 **Oblique Camera Angles**: When the camera is angled acutely to the ground surface the drone will naturally image regions outside of the survey area. Separate flight paths might need designing to capture these low camera angle passes (e.g. Waypoint surveys).

3 **Topographical Hazards**: It is important to establish a minimum safe altitude within each survey zone to ensure that the drone will not collide with the ground or other hazards. GS Pro records altitude as meters above the take-off (relative, not absolute). It is good practice to take-off and manually fly the drone to the highest point in the survey area and use the drone's recorded altitude plus a safety margin to determine a minimum safe altitude.

4 **Relative Altitude**: All altitudes entered into GS Pro are required to be a positive number. As such, take-off locations must always occur below the intended flight path of an area/waypoint survey. This can prove problematic when working with cliff-sections accessible from the top, but not bottom of the section.

3.3. Survey Design in GS Pro

In GS Pro it is possible to outline a survey area on top of satellite imagery. The software will provide you with a time estimate for the survey as well as the number of photos that will be taken. The survey can be customised to control the altitude, image overlap, speed of flight, camera angle and many more variables. When planning, placeholder values must be chosen for flight altitude and overlap (the main two controls on survey time and image output).
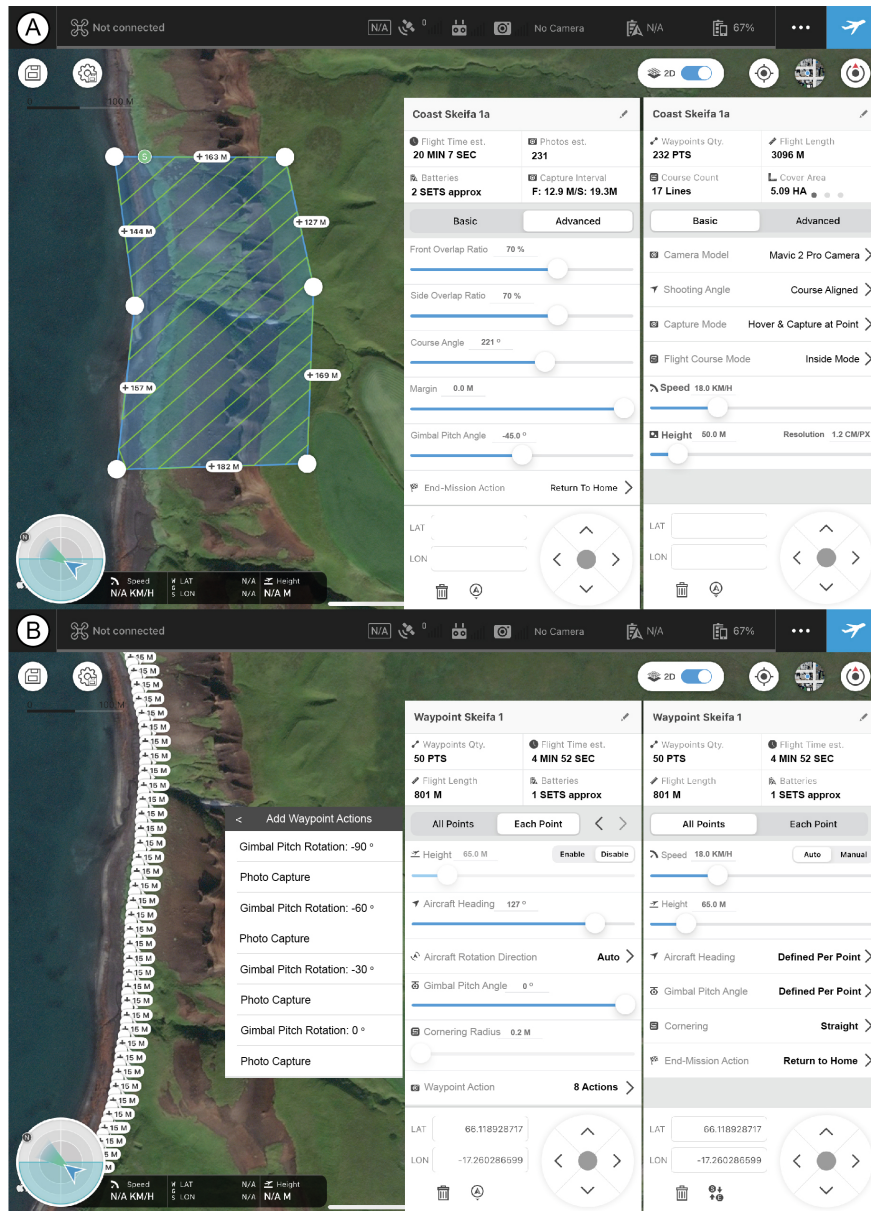
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Figure 5: Screenshots of DJI's Ground Station Pro software for autonomous survey planning. (a) Area Survey (b) Waypoint Survey with nodes spaced every 15 m. Key variables for both survey types are shown as they would be in the software.

These placeholders will be updated once an in person assessment of the field area has been made. For this project, it was decided that an altitude of 50m and overlap of 70% provided a good balance between image density and the total area that could be feasibly surveyed within our three week time-frame for fieldwork.

Areas of very complicated geometries or areas where high model fidelity is desired, should be identified as part of the planning. These areas might require manual flight and image capture to ensure that the resulting 3D model captures all necessary details. Due to the flexibility of Agisoft's photogrammetry software, detailed images taken closer to the exposure will have the effect of only increasing the model fidelity in those regions. This allows for targetted surveying within a wider, lower resolution canvas outlined by the automated area and waypoint surveys.

Whilst planning our survey it was decided that for every three days in the field, 1 of those days should be put aside for potential bad weather. This proved a practical division of time. Over any consecutive three day period of our fieldwork the maximum, minimum and average flight time achieved were 10.1, 4.3 and 6.8 hours respectively. Carrying 9 batteries every day, it was realistic to target 6 hours of flying within a 72 hour period. Should weather be more reliable, it is of course possible to more generously allocate flying time. The data collection for the Tjörnes Beds model took place over a 15 day period.

It is recommended to build a survey program for the available field time, striking a balance between area to be surveyed and the desired detail of the survey. Careful book keeping of flight times compared to estimates within GS Pro will allow effective decision making and realisation of survey goals, an example of how to record flight information can be found in Table 3. GS Pro provides an idealised time estimate but once wind, altitude and air temperature are considered the actual survey time will be greater than the prediction. It is also worth noting that GS Pro predicts waypoint times without accounting for the action times at each node. Area surveys were found to take 27% longer than predictions (sample size: 35 area surveys) and waypoints took 290% longer

(sample size: 16 waypoint surveys, with 4 images at each node).

The flight altitude required by GS Pro should incorporate a Minimum Safe Altitude (MSA) for the area being surveyed. The MSA is representative of a altitude clear of any obstructions, hazards or topography. The MSA can only truly be assessed at the survey site once the local area has been inspected. The Mavic Pro 2 records it altitude relative to its take-off altitude (take-off $= 0$ m), resulting in the final survey altitude and MSA being relative to this datum. Whilst the Mavic Pro 2 can be flown manually at negative flight altitudes, GS-Pro will only execute surveys with positive altitudes. This requires take-off locations to be below the planned survey altitudes. To safely and reliably assess the MSA in person, it is recommended to manually fly the drone to the highest topographical point in the survey area and read off the altitude from the drone, this can be used to establish an MSA.

Name	Survey Type	Flight Times (min)		Flight Altitudes (m)	
		Estimated	Actual	Take-Off (ASL)	Survey (RTO)
Survey 1	Area	12 : 40	16 : 20	5	55
Survey 2	Area	15 : 20	19 : 20	35	25
Survey 3	Waypoint	15 : 20	...	...	...
...	...	...	...	...	...

Table 3: An example of how to record flight information for a photogrammetric survey. Tracking estimated vs. actual flight times will allow for important assessments of survey progress to be made and can also inform future flight time estimates. It is recommended to record two sets of altitudes, the take-off altitude (metres above sea-level - ASL) and the survey altitude (metres relative to take-off - RTO). These two altitudes contain all the necessary information to asses the true flight altitude of the drone for any given flight.

3.4. Camera Settings

The camera provides the main means of data collection for SfM surveys and as such needs to be configured in an idealised manner. The desired outcome is one where as much of the image is in focus as possible, motion blur is minimised, exposure is correctly balanced and the white balance is consistent shot to shot. A digital camera offers a range of settings to control the above parameters, however they operate in a somewhat coupled manner, as outlined below.

Digital cameras are primarily controlled by 4 settings. Aperture, shutter speed (exposure time), ISO (film speed) and white balance. The aperture represents the iris of the camera lens and dictates how much light enters the camera. It also controls the depth of field of an image, such that an open aperture (small f-number) sees greater background blur (low depth of field) and a softer image than closed aperture (larger f-number), which produces an image that is sharper and more widely in focus (high depth of field). Shutter speed represents how long the sensor of the camera will gather light for. The greater (slower) the shutter speed, the brighter the image and the more motion blur that will be captured by the sensor. ISO represents how sensitive the sensor of the camera is to light. The higher the ISO the brighter and more noisy the image. White balance instructs a digital camera as to the qualities of the colour white in the imaged scene. White will look different under direct sunlight when compared to the same white under a fluorescent lightbulb. White balance can drastically change the colours of an image.

To create a sharp, mostly in focus image requires as small an aperture as possible (large f-number). To capture minimal motion blur the shutter speed needs to be as short (fast) as possible and to minimise noise it is desirable to keep the ISO as low as possible. However, all three of the end-member settings outlined above will result in very little light reaching the sensor and the image can end up under exposed. All images represent a compromise between the three settings outlined above.

The advantage of GS Pro and automated surveying, is that the drone can

repeatedly stop and hover to take each image. Once hovering, the gimbal allows for a very steady camera platform, minimising motion blur and allowing for slower shutter speeds than for a drone in motion. Typical shutter speeds were found to be between 1/50 - 1/150 second. The slower shutter speeds without having to compromise on motion blur, allowed for the use of smaller apertures (greater f-numbers) resulting in sharper, more in focus images. In the same manner, the brighter images afforded by slower shutter speeds allowed for ISO values typically below 400, aiding in noise reduction. White balance should be manually adjusted to suit the daily changes in sunlight and weather. This will ensure colours are as consistent as possible across multiple images.

Weather and light play an important role in aerial photography. The ideal conditions results from an overcast day where the light would be described as "flat". Harsh, direct sunlight results in overexposed highlights, glare and severe shadows. The orientation of the exposure will also influence what time of day provides optimal lighting, for example a westward facing cliff section should not be surveyed in the morning as the camera will quickly become overwhelmed by the lighting conditions of having to image a target in shadow whilst still receiving direct sunlight on the camera sensor.

A final choice of image file can be made. Drones will typically save images in JPEG format, but it is possible to shoot in RAW. RAW offers greater flexibility when editing images. However, RAW produces much bigger file sizes and will need editing and exporting to a JPEG before use in SfM software. The survey of the Tjörnes Beds produced c.17,000 JPEG images, the file size of each image ranged between c.7-16 MB, see Fig.2. It was not considered worthwhile to edit every RAW image for the small gains in image quality it would provide. Making careful adjustments of camera settings throughout the survey resulted in clear and high quality JPEG images, allowing for a straightforward import of the data into post-processing software such as Agisoft Photoscan.

3.5. Data Collection

Once in the field, data collection can begin. If an automated workflow through GS Pro is used, the drone will complete almost all the work autonomously. This can be monotonous work, but it is important to stay vigilant regarding the weather, drone status and any other hazards that may present themselves. In our experience, large birds of prey will get aggressive with drones. When conducting our survey, drone operations would be paused should the local falcon be spotted whilst it passed through the area.

Due to planning of the survey taking place with placeholder altitudes and overlap values, these will need to be updated before each survey begins in the field, incorporating an assessment of the MSA. Prioritising timekeeping proved pivotal in successful imaging the total survey area, as such adjustments to the altitude and overlap should be made to keep the image count (and by proxy, flight time) as constant as possible. By targetting a constant density of photos in a given survey area, longer duration projects can be kept on time whilst adapting quite flexibly to the demands of the local topography and exposure. If diligent planning is undertaken, then the workload in the field is relatively light, leaving ample head-space to focus on monitoring the safe operation of the drone.

A large amount of data is produced by these automated surveys, this project resulted in 215 GB of JPEG images. It is important to systematically store these data. It is recommended to offload all images from a day's surveying from the drone's onboard SD card to an external hard drive, as recommended in Table 1. The SD card should be cleaned/emptied of backed up images to maximise the available storage space for the following day's work. It is helpful to store images in a folder structure that matches the flight logs, ensuring data can be easily located and post-processed. It was helpful to have a laptop capable of processing the drone imagery during the fieldwork period in order to quality check the resulting 3D models and identify areas that may need re-surveying or areas that require changes in the survey design. Our project utilised an

Alienware M15, core i9 laptop with 32 GB of RAM and an NVIDIA 3080 Ti (Table 1).

4. Data Processing

The workflow presented here is conducted using Agisoft Metashape Professional with the end goal of uploading the exported model to V3Geo for hosting on (VOG Group, 2022a). As such, parts of the workflow are designed specifically to cater to the requirements of uploading to V3Geo's servers. Full details of V3Geo's submissions guidelines can be found at the following address https://v3geo.com/contribute. If the survey area is large enough, it will be necessary to split the overall model into small zones, each processed individually. Below is a step-by-step guide to creating a 3D photogrammetric model.

4.1. Align Photos

The first step with any Agisoft project is to load the photos into the project and align them. Agisoft guides the user through the software through the "Workflow" menu. Options will become explorable once the necessary steps in the workflow have been conducted in the correct sequence (e.g. you cannot build a mesh without having first imported and aligned images). GPS information will be read from the photo metadata and be used to locate and scale the model space.

The first stage in the creation of a SfM model is to create a point cloud, representing a set of data points typically located within a Cartesian space. The *entire* image dataset will be aligned in one step to produce a low density point cloud of the entire survey area. The low density point cloud (and the associated images) can now be split into smaller regions, termed here as "subzones", each processed individually. Each sub-zones should be stored within their own "chunk" in Agisoft. The reason for creating sub-zones is to ensure that memory requirements are not exceeded whilst processing within Agisoft and to match any eventual upload limits provided by the eventual destination/host of the model.
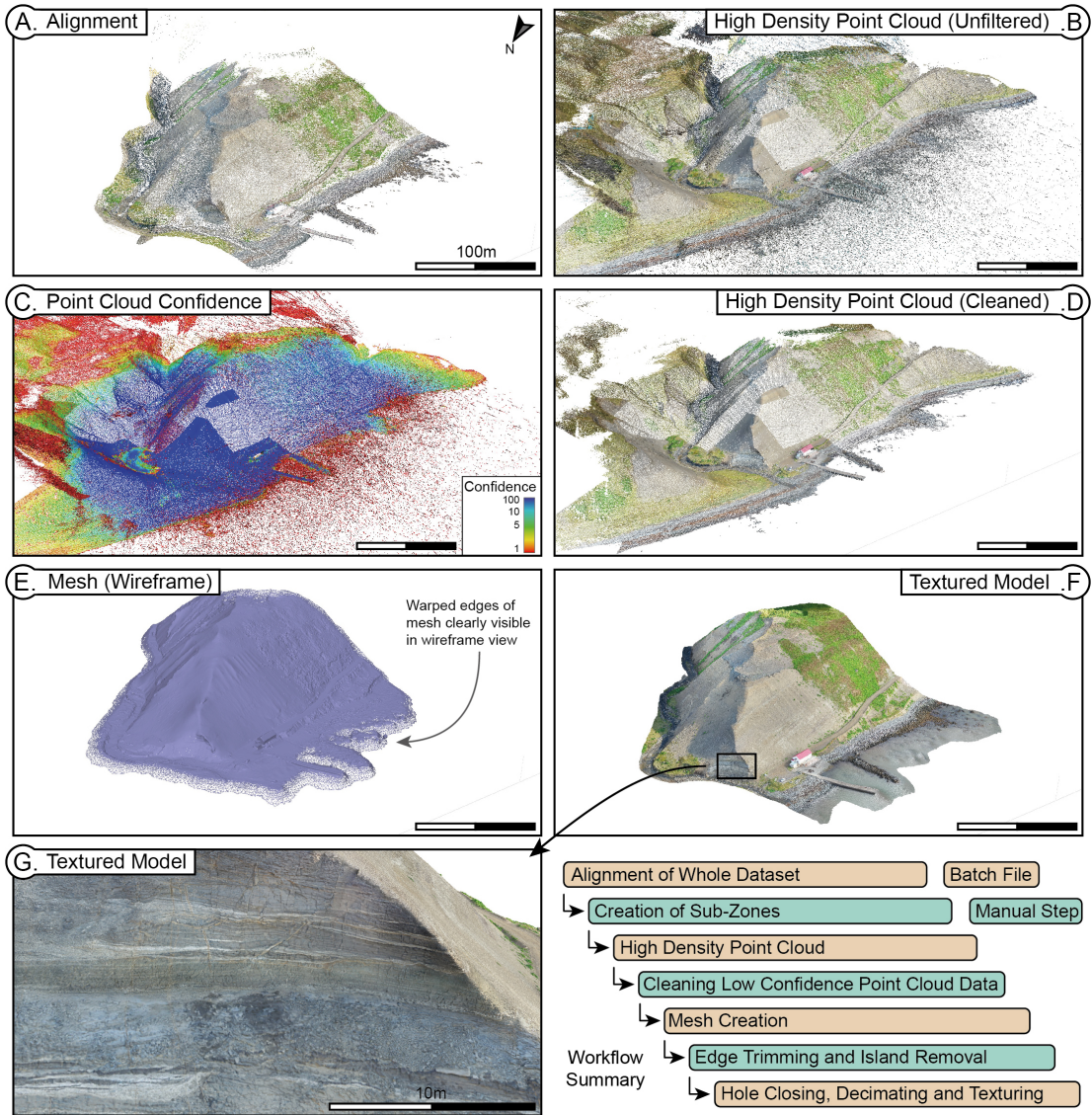
Figure 6: Proposed workflow within Agisoft Metashape for a single sub-zone of the aligned model space. (b) A high density point cloud is constructed and (c) low confidence points are (d) cleaned (shown: cleaned below confidence = 2). (e) The resulting mesh is then trimmed to removed warped edges and mesh islands are identified and removed. Holes in the mesh are closed, the mesh is decimated and textures applied for a finished model (f). (g) a close-up of the final textured model highlighting the sedimentary structures visible in the model.

The low density point cloud produced in the alignment stage should bear a fuzzy resemblance to the entire surveyed area. It is important to align the entire dataset before the creation of sub-zones to ensure accurate meshing of the sub-zones following the creation of the final textured models. The low density point cloud should now to be sampled into the sub-zones by duplicating the entire dataset and deleting all cameras and point cloud data outside of the respective sub-zones, Fig.6a. A small amount of margin/overlap should be left between sub-zones, this is important to create clean edges to the eventual textured model mesh.

You should now be left with one chunk containing an aligned, low density point cloud constructed from all the images of the whole survey area and a series of chunks representing sampled sub-zones that cover the extent of the whole survey area. Each of sub-zones will now be processed further.

4.2. High Density Point Cloud

The next step in the Agisoft workflow is to generate a high density point cloud for each sub-zone, Fig.6b. When building this dense point cloud, ensure that confidence values are calculated for each point, this will prove important. Once created, switch to a view of the point cloud where each point is coloured by its confidence value, Fig.6c. The actual exposure should be visible underneath a haze of low confidence noise. By using Agisoft's filtering options (Tools −> Dense Point Cloud −> Filter by Confidence), it is possible to view and delete these low confidence points, revealing the target exposure, Fig.6d.

Experience revealed that points below a confidence of 2 offer very little to the end product. Filtering and deleting points between a confidence of 0-2 removes most of the noise produced when generating the high density point cloud. Points of confidence between 2-5 can often be deleted for gains in eventual textural quality. However, in areas of complicated geometry (e.g. craggy cliffs or overhangs) confidence will be naturally lower. Assessment may be required when deleting points between 2-5 confidence to determine if they represent useful information or noise. The fidelity of the model texture is also linked to the size

of the model being processed, so breaking the sub-zones into smaller areas will increase the detail of the final product. As a reference, sub-zones for the Tjörnes Beds model were composed of high density point clouds of c. 1,000,000 points.

4.3. Mesh

Once the cleaned, high density point clouds have been created, the clouds need meshing into a surface. The edges of the resulting mesh can become warped due to a lack of data at the edge of each sub-zone, Fig.6e. If appropriate overlap has been left between neighbouring sub-zones, then this warping can be trimmed to leave a clean surface which will mesh indistinguishably with adjacent sub-zones. This warping is particularly visible if the mesh is viewed as a wireframe, whereby the density of the frame drastically reduces as it approaches the warped edges.

Some part of the mesh may form "islands". These are floating and undesirable parts of the model created when the underlying point cloud data is inaccurate or too noisy to resolve the true geometry. These islands can be removed using Agisoft's Gradual Selection tool (Model $->$ Gradual Selection $->$ Connected Component Size). This tool allows for selection of the mesh based on a finite number of connected parts, making island's very easy to select and delete.

Once the mesh is trimmed, any holes in the mesh will need closing, this can be done with Agisoft's "Close Hole's" feature. Now the mesh is trimmed and free of holes, it needs decimating to achieve the desired file size of the upload destination. For example, V3Geo requests individual uploads do not exceed 300 MB. The mesh represents a series of triangle, or faces, which approximate the geometry of the modelled landscape. Higher face-counts result in higher fidelity models but at the cost of larger file sizes. The mesh can be decimated, to reduce the face-count and subsequent file size. It was found that decimating each sub-zone to a face count of 3,000,000 kept each sub-zone below V3Geo's 300 MB upload limit.

4.4. Texture

The final stage is to apply textures from the drone imagery to the blank mesh, Fig.6f. At this stage it is useful to explore all points of the models and check that the quality of the texturing is as desired. Depending on the destination of the model, there may be limits on the textural settings that can be applied. It is also sensible to combine each zone with it's neighbouring zones and assess the quality of the boundary mesh. If done correctly, the seam should be invisible. Before export, it is important to check if the models need translating (x,y,z), as you might find a known datum (e.g. sea-level) which is not quite at the correct altitude. This can be adjusted in the model export options.

4.5. Batch Processing

Depending on the size of the survey area and desired model quality, processing steps can take several hours to complete. It may be necessary/practical to batch process the SfM workflow outlined above. For example, creation of high density point clouds for the Tjörnes Beds model took up to 5 hours for each of the 24 sub-zone on a dedicated workstation. Four Agisoft Metashape batch files can be found at the GitHub link in the supplementary information of this paper, containing all the settings used for the creation of the V3Geo Tjörnes Beds model. Creation of the sub-zones, manual removal of low confidence point cloud data, trimming of the mesh edges and island removal all require manual input and so are not included in the batch processing files. These four files can be loaded and executed in Agisoft, interspersed with the manual input steps. An outline of this workflow is included in Fig.6.

5. Summary

In this paper a practical guide is presented for the collection and processing of drone based imagery in order to produce large scale SfM 3D models. The workflow is structured around the DJI Mavic Pro 2 and using DJI's GS Pro

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software to create and execute automated aerial surveys. An emphasis is placed on flight planning to balance time keeping, survey scale and model fidelity.

Image processing occurs with Agisoft Metashape Professional. A workflow is outlined to batch process and produce large scale, high fidelity (sub 5cm resolution) SfM 3D models for uploading to cloud based/online hosting platforms such as V3Geo. Batch processing files are provided, allowing for the results of this paper to replicated.

6. Supplementary Information

The Agisoft Metashape batch files to replicate the workflow outlined in this paper can be found at the following Github link:

https://github.com/doughface01/Agisoft_Metashape_SfM_Batchfiles

7. Acknowledgements

8. Author Contributions

Matthew Allison Methodology, Investigation, Data Curation, Writing - Original Draft, Visualization. **Jonathan Hall** Methodology, Investigation, Writing - Review and Editing. **Stephen M. Jones** Writing - Review and Editing, Supervision.

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