Photogrammetry:
A guide to good practice

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Photogrammetry: a guide to good practice

1. Introduction to photogrammetry

Photogrammetry is a field of technology in which photographs are used for various kinds of measurement. Photogrammetry can be used to determine the exact positions of geographical features (for example for topographic maps), and to create rotatable 3D models of photographed objects or various types of 3D visualizations. This guide aims to provide guidance on what to consider both before and during the documentation and archiving of datasets produced using digital photogrammetry. The guide covers common file formats used for storing photogrammetry files and which of these are suitable for archiving. The guide also discusses archiving strategies that can be used to ensure that the quality of photogrammetry files is maintained after preparation for archiving. The guide builds on existing documentation standards and describes the photogrammetry data that is considered to be important to preserve for future use.

Photogrammetry can be performed from a long distance, for example from a drone or an aircraft, or at close range with a handheld camera or a camera on a tripod. Data collection with drones or aircraft often results in exceptionally large data sets and requires (to some extent) different data management than data collected with ground-based photogrammetry. The guide is therefore limited to ground-based photogrammetry, performed at close range with a digital camera.

Structure-from-Motion (SfM) is a common branch of photogrammetry. SfM is based on the same principles as other photogrammetry and aims to create 3D models but is more user-friendly and has lower accuracy requirements. For example, SfM does not require camera calibration or advanced camera equipment. The guide is also aimed at people working with SfM, and the information about file formats, metadata and significant properties is the same for anyone working with photography-based 3D reconstructions, regardless of the level of accuracy.

1.1 What is photogrammetry?

Photogrammetry is an umbrella term for various types of measurement that may be made using photographs. Photogrammetry as a field of technology was invented in the 19th century, and various methods were developed during the 20th century. In simple terms, there are three branches: *analogue*, *analytical* and *digital* photogrammetry.

- **Analogue photogrammetry** reproduces image orientations mechanically or optically in analogue stereo instruments.
- **Analytical photogrammetry** reproduces them mathematically, and the images are mechanically corrected in their placeholders during measurements in analytical stereo instruments.
- **Digital photogrammetry** uses only digital methods to reproduce and present image geometries.

The digital branch has more or less replaced its analogue and analytical predecessors, and the photographs used are almost exclusively in digital form.

Photogrammetry can be used to determine the size, shape and position of the objects depicted. Photogrammetric measurement can be performed from a single image, from a pair of images (stereo) or from a block of images (three or more photographs). 3D models generated using methods other than photogrammetry (for example 3D graphics for computer games) usually consist of an underlying geometry on top of which various textures and material properties are applied. A photogrammetry model takes its shape through triangulation.[1] The different positions of the camera in relation to the photographed object determine the shape of the 3D object. 3D models created with photogrammetry retrieve texture information directly from the photographs. The result can therefore be very lifelike and similar to the original.

Figure 1: When an object is photographed from two or more angles (and the images overlap by at least 50%), the information can be used to perform various types of calculation or to create 3D visualizations of the photographed object.

Areas of application

Photogrammetry is used as basis for research, as a documentation method, or to generate 3D visualizations that can be used to show what something looks like or will look like. It is used in areas such as earth sciences, cultural heritage, architecture, criminology, and the industry. Photogrammetry may be combined with other techniques such as motion capture, GIS, BIM, or CAD. Unlike laser scanners, which can be expensive to acquire, photogrammetry is a relatively cost-effective technology and, in some cases, can replace the laser scanner as a documentation method. All you need is a reasonably good quality digital camera and a computer with photogrammetry software. The advantage of a 3D photogrammetric model over two-dimensional raster images is that it allows a viewer to turn the model around and study it from many angles. It is thus an educational and very effective tool for communication.

The use of photogrammetry in the field of cultural heritage is becoming increasingly common and is rarely limited by the size of the objects to be documented. Three-dimensional photogrammetry models can be created of anything from small objects, such as coins or worked stone tools, to entire buildings and monuments. An example in which photogrammetry has been used to document an exceptionally large object is the reconstruction of a statue of Buddha in Afghanistan. The statue, which was 53 metres high and carved out of a rock face, was blown to pieces by the Taliban in 2001. After the blast, a team of researchers from ETH Zurich collected photographs from private individuals (via the internet) and supplemented them with holiday photographs taken by a tourist in
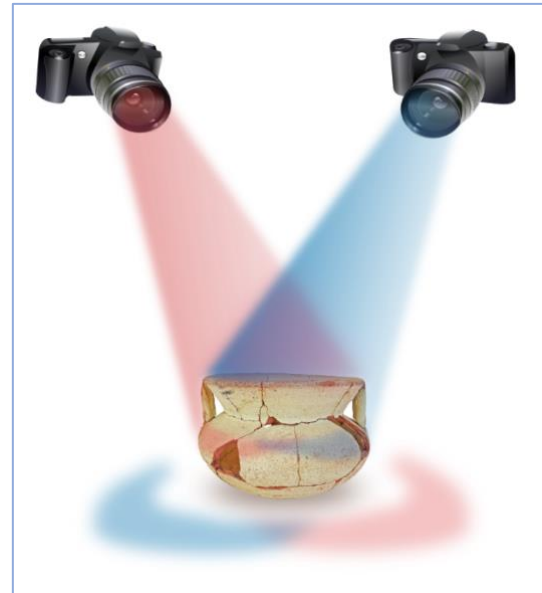
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[1] https://en.wikipedia.org/wiki/Triangulation. Accessed 22 February 2023.

the 1960s. They had a large enough base to create a photogrammetric model of the statue. From the 3D model, it was then possible to create a physical reconstruction (scale 1:200).[2]

1.2 Things to consider

The choices made at the beginning of the project will shape the entire photogrammetry process and influence the final product. For example, it is possible to use a mobile phone camera to create 3D photogrammetric models (and depending on the level of ambition, the result may be good enough), but it can never be compared to a model created using a calibrated system camera.

High-resolution images take longer for a computer to process, but will result in a more detailed, high-resolution model. The number of images taken also has an impact on the finished model. If you know that there will not be another opportunity to photograph the object you want to make a 3D model of, it is better to take too many pictures than to take too few and then regret it if the result is not good. This guide assumes that the level of ambition is high and that the aim of the photogrammetry is to document an object so accurately that it can be used for further research. The various steps that may be involved in the process of creating a photogrammetry model and the considerations associated with each step are given below.

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[2] https://www.research-collection.ethz.ch/bitstream/handle/20.500.11850/147846/1/eth-26930-01.pdf. Accessed 16 August 2022.

2. Things to consider when creating 3D models with photogrammetry

2.1 General considerations

Each photogrammetry project should include project-level documentation of the project, project title, names of all participants, dates, and other useful notes. To ensure that the files can be understood and used in the future, very extensive documentation is needed.

2.2 Photogrammetry methods

Camera calibration

Many common digital cameras have proven useful for photogrammetry, but the results vary, depending on the model, lens choice and pre-sets. There are *metric* and *non-metric* cameras. In simple terms, non-metric cameras include virtually all digital cameras (including system cameras) that can be purchased for private use, while metric cameras are designed specifically for photogrammetry and are considerably more expensive. Metric cameras are calibrated to take precision photographs with less lens distortion than a standard camera. Both types can be used to advantage for photogrammetry and, regardless of the type of camera, camera calibration is an obligatory step to ensure that the photographs taken are of sufficient quality. Camera calibration allows the internal parameters of the camera to be measured in advance, thereby correcting distortions caused by the lens (for example curvature of straight lines).

When a camera takes a picture, light from a 3D scene is converted and saved as a 2D image. Each pixel in the image can be said to correspond to a pin of light in the real world. The camera calibration process determines which incoming light is associated with which pixel. Distortions (or other errors) resulting from the lens may, in a worst case scenario, result in distortions in the image, which will complicate the process of transforming the 2D images into a 3D model.[3] By calculating the lens and image sensor parameters of a camera, such distortions can be corrected. In some photogrammetry projects, two different cameras are used to create a stereo image of a given object. The camera calibration helps to correlate the projection matrices of the different cameras and calculates the 3D coordinates of a point seen by both cameras. Camera calibration may be performed automatically, semi-automatically or manually. Each calibration is unique to a particular camera and lens combination and does not apply to other cameras or lenses. Changing the zoom of the lens will require recalibration because the internal parameters of the camera have changed. It is recommended to maintain a fixed focus during both calibration and photography.

For a list of camera calibration metadata, see section *3.3 Camera metadata*.

Image capture

If the aim of the data creator is to create a 3D model, the object needs to be photographed from many angles. You should make sure that the images overlap by at least 50% because the software that builds the model looks for key common points (often corners and angles) in the images. For a point to be included in the final 3D model, the exact same point needs to be visible in several images (at least two).

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[3] http://mixedreality.wikia.com/wiki/Camera_resectioning. Accessed 16 August 2022.

If the image capture process is not sufficiently well documented, there is a risk that people who were not present when the images were taken will misunderstand how the images fit together. Any information that makes it easier to understand each image therefore needs to be documented. Examples of tools to create context include placing a scale marker (such as a metre stick or ruler) or a north arrow next to the object being photographed. In addition, notes on the orientation of each image are needed ('the camera is facing west'). If geographical information is needed to understand the photogrammetry object, there should be a map of the location on which the object is marked and preferably a list of measured coordinates.

Most digital cameras can store metadata in what is known as EXchangeable Image File Format (Exif)[4] and it can be accessed via many image processing applications (see also section *3.3 Image metadata*). Exif is a specification that relies on metadata information being stored with the file format. In practical terms, this means that image facts are automatically recorded and stored in the image file for use in, for example, archiving. Camera manufacturers also save most of the camera's settings, including model, version, image rotation, aperture, shutter, focal length, white balance, light metering method, ISO, whether the flash was used, distance from the subject, and anything else related to the moment in which the photo was taken. Previously, Exif did not support JPEG 2000 and PNG formats, but now Exif supports most of the most common image file formats. Users can add their own metadata to Exif, such as the name of the originator.

One problem with the specification is that image processing applications do not always handle Exif metadata correctly. If the image is modified in an image processing application, the information may be destroyed or distorted. Some photogrammetry applications (such as Agisoft PhotoScan) use the accompanying Exif metadata when converting images and, if this information is corrupted, it can cause problems for the application (Bennett 2015). Therefore, never modify any of the original images. It is better to make a copy if you suspect that you need to process an image.

Reference system, orientation, and accuracy

For photogrammetry, it is not always necessary to know the exact location of the object on the globe. The importance of this varies between projects and depends on the object to be documented. For example, it may not be necessary to refer the object to a place if the object is a vase or a figurine. However, if the object is a building and the information about the location of the building is deemed important, all data collected must be oriented in relation to a reference system, either at the image capture stage itself, or afterwards on a computer. There are two reasons for linking orientation data to a photogrammetry project:

1. to provide information about the position of the object within a reference system, and/or
2. to set geometrical boundaries for the photogrammetry model.

SWEREF 99 is the official reference system used in Sweden. SWEREF 99 is a (geodetic) three-dimensional reference system. Its three-dimensional nature can cause difficulties and, to avoid excessive margins of error, the two-dimensional national map projection SWEREF 99 TM is used for national applications. For local level applications, twelve local projection zones are also available.

To determine the position of the photographed object, it is necessary to integrate enough measured reference points in the project. The reference information may be in the form of control points

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[4] https://en.wikipedia.org/wiki/Exif. Accessed 22 February 2023.

(photo-identifiable points with known coordinates), deployed photo-identifiable objects (for example chequered sheets of paper) and/or photo-identifiable angles.

Since photogrammetry models lack scale information, the data creator has to define the scale so that the size of the model can be determined. This can be done in different ways. Common approaches are:

- A ruler or stick of known length (such as a metre stick) is placed in front of/next to the model.
- The length of the object is measured for two or more photographs.
- The relationship of the object to two known control points is used as the basis (the distance between them can then be measured).

A scale indicator may be inserted to determine the scale more precisely. If such reference information is used, this should be documented along with the accompanying metadata. The degree of accuracy determines how accurate the scale information for the photogrammetry model will be but does not affect the shape of the model.

In order to determine the orientation of the photogrammetry model within the selected reference system, at least two known 3D control points (control points with X, Y and Z values) and one control point with at least one known coordinate (X, Y or Z) are needed. Control points are identification marks with known coordinates that are either directly on, or adjacent to, the object to be documented. Choosing appropriate control points both simplifies the working process and provides more accurate results (Wenhao 2001), which is crucial if the model is to be used in conjunction with GIS data. The reference information may also be in the form of observations with slightly lower accuracy if there is no requirement for higher accuracy. If only two GPS-measured control points are used (with 1-metre accuracy) with one known elevation value, the scale of the model can be determined by the calculated distance between the GPS points. The position could also be determined based on the two control points with the elevation value. Providing only minimal reference information (i.e., two 3D control points and one 1D control point), apart from scale information, will only influence the position and orientation of the photogrammetry model within the selected reference system. The accuracy of the distance, angles and shape of the 3D model is still determined entirely by the photographs captured. If more than minimal reference information is provided (three or more 3D control points), this information can also be used to define the shape of the photogrammetry model. If this is the aim, the data creator must ensure that the reference information has at least three times the positional accuracy of the photogrammetry model itself. Otherwise, there is a risk that the reference information will distort the model. In practice, this means that if the internal accuracy of a photogrammetry model is at a scale of 1:1000, the reference information should be accurate to at least 1:3000.

In projects in which reference information has been integrated in the photogrammetry model, the relevant metadata should be documented and deposited with the associated data (see also section *3.3 Reference system metadata*) for archiving.

Image processing
In some cases, some form of digital post-processing of the photographs is required. Image processing includes all forms of adjustment to brightness, colour, contrast, definition, etc. It is worth bearing in mind, as mentioned in section *2.2 Image capture* (see above), that many image processing

applications may distort the Exif data associated with the image and that this may complicate the process of converting 2D to 3D. Therefore, careful consideration should be given to whether image editing is really needed. If it is deemed necessary, an unedited original version should be saved/archived. It is important to point out that an image to be used for photogrammetry must **never** be cropped.

It may sometimes also be necessary to convert a digital image from one format to another. The original images should then be saved in their original, unedited state and stored separately. If the camera used is set to take images in its own RAW format, these should be converted to an archive format before submission for archiving (for example Nikon RAW .nef can be converted to Adobe .dng using Adobe DNG Converter). The name 'Raw' comes from the fact that image files in RAW format are completely unprocessed and are therefore not ready to be edited in an image processor or printed. Due to the lack of standardization and the large number of RAW formats, it is almost impossible to characterize a RAW file. Many files are uncompressed, while others may use both destructive or lossless compression (and some allow the user to choose). The lack of standardization also means that many files require special software to be read. RAW image files are sometimes referred to as digital negatives, as they perform the same role as negatives in analogue photography. That is, a negative cannot be used directly as an image, but it contains all the information needed to create an image and the image quality is not likely to deteriorate if adjustments are made to, for example, white balance or exposure. For dissemination and archiving, it is not recommended that files be saved in RAW format, but make sure you document all image format conversions and the software used to perform the conversion as these may have an impact on image quality.

### How to create a three-dimensional photogrammetry model
In the example below, a simple 3D reconstruction of a toy dog has been carried out using SfM. The 3D model was generated from about 200 images taken with a standard mobile phone camera. The model should not be seen as an example of how a photogrammetric 3D model should be created (the opposite case). It is used here as an educational tool to illustrate the different stages that may be involved when a 3D model is generated. The 'may' is because the process may differ from application to application. The model in the example was generated in Agisoft Photo Scan.

Step 1: Image adjustment
Image adjustment is the step in which the photographs are uploaded to the photogrammetry application and transformed from 2D to 3D. The images need to overlap by at least 50%. The application searches for common points and traces prominent geometrical elements such as corners and angles. When a corresponding point has been found in two or more of the images, the application compares the colour and texture in the immediate proximity of each point and obtains an average value. The different positions of the camera in relation to the photographed object are important, both to find common points, but also to calculate depth information for each point based on the estimated camera positions. This is one of the prerequisites for the transformation from 2D to 3D to be possible. Measurements of the distance from the cameras and colour information are combined into a three-dimensional point cloud in which each point represents the average value of the points traced. The more common points that are found, the better the conditions for a good 3D reconstruction are. Incorrect image adjustment where the application does not find common points is usually the result of poor overlap, the object not being in focus, the volume of texture detail on

the object surface being insufficient or the light being too poor (for example, too much contrast between highlights and shadows).

On the next page you can see what the first point cloud for the toy dog looked like. *Figure 2* was generated from about 200 images and the shape of the object can be detected, but in the 'air' around the object there are points (noise) that do not belong to the object. The mobile camera used did not always manage to focus on the dog and the noise is probably due to the focus being on different areas of the images. Further aggravating factors were that the dog had many smooth,
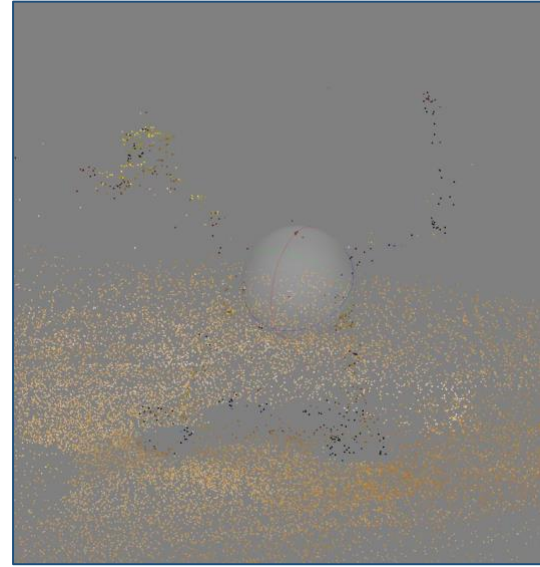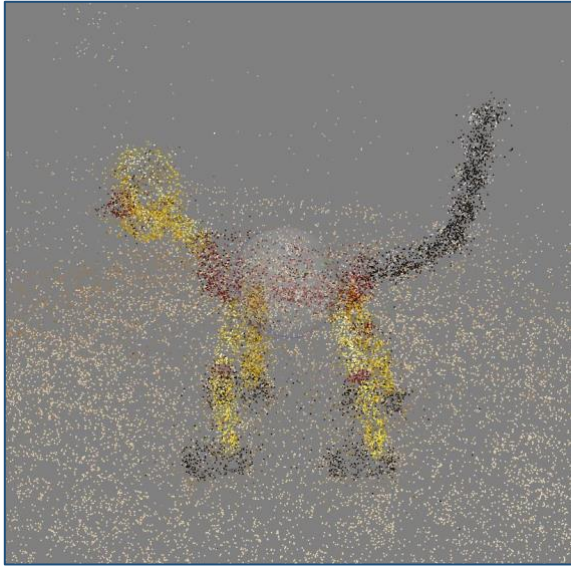
Figures 2-3: Figure 2 (left) shows the point cloud generated from 200 images. Figure 3 (right) shows the same object, but this time only 30 images were used.

monochromatic surfaces and that the surface was glossy (see *Figure 9*). Some applications can reduce noise automatically, but here the points were manually edited out before the next step was taken. For comparison, *Figure 3* was generated from only 30 images. This was far too thin a basis for this object with the camera used. The result was that the application could barely find enough common points to make a guess at the shape of the object.

Step 2: Compact point cloud

In the next step, the point cloud is densified. A point cloud is essentially a large collection of points placed in a 3D space based on an arbitrary three-dimensional coordinate system. Generating the compact point cloud is probably the most time-consuming part. It is also only now that we get a first glimpse of what the 3D model will ultimately look like. If there are gaps, the application has not found any common points in that area, which is a problem that will also be present in the final product. If you are lucky, the texture from the photographs may hide the flaws in the geometry, but it is advantageous if the compact point cloud is evenly

Figure 4: The toy dog has several small holes in its body (including in its face), which shows that the application has not found any reference points in those areas.

distributed over the whole model and gives the impression of a solid model. There should ideally be no gaps or deformed areas.

Step 3: From point cloud to mesh

After the compact point cloud has been generated, it is possible to create a vertex-based[5] mesh model. A mesh model is constructed from a network of polygons based on the compact point cloud. At this stage, the geometry of the object is described by dividing the surface into a mesh of triangular polygons that are either hollow (see *Figure 5*) or filled in. This step may be compared to a three-dimensional version of joining the dots and seeing a picture emerge.

Figure 5: A close-up of what the mesh model looks like after the application has generated polygons from the point cloud.

For *Figures 6–7*, the polygons have been filled again. The model is displayed here in a neutral colour, or RGB information is taken from the photographs. RGB information is not the same as texture information having been retrieved. This reveals even more clearly whether there are any flaws in the geometry. Photogrammetry applications can correct such deficiencies retrospectively to varying degrees. It may be possible to correct imperfections and fill in holes manually, but it is best if enough overlapping images exist so that voids, or other distortions of the geometry, can be corrected automatically. The application may also have created more polygons than necessary, in which case there are various polygon reduction applications that can help reduce the number of polygons.
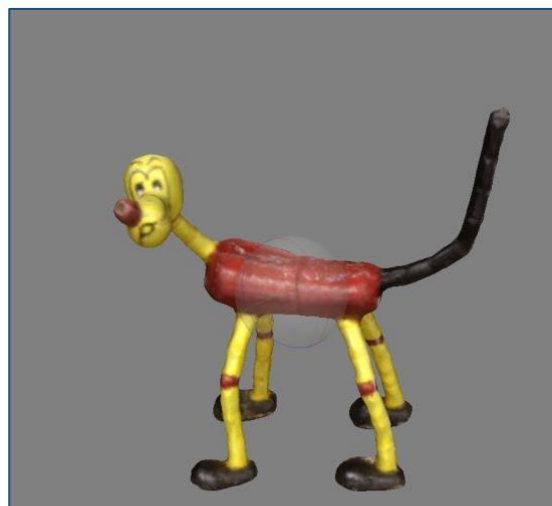
Figures 6–7: Two versions of the model are shown here with the polygons filled in. You can see that the geometry still has some shortcomings.

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[5] Vertex describes the point at which two sides of a polygon meet, i.e., the corner of the polygon. Vertex-based models use plane polygons, triangles, or rectangles, to represent rounded shapes.

Step 4: Texture

In this step, you can retrieve texture information from the photographs and apply it to the model. If previous steps have been successful, the 3D model will now have a photorealistic appearance. Further steps can be added such as manual adjustments, animations, motion capture and so on but, generally speaking, this step is the last one that completes the 3D reconstruction.

Figures 8–9: Figure 8 shows the finished result with texture taken from the photographs. The automatic settings have been selected. Figure 9 shows one of the original photographs used.

3. Archiving photogrammetry data

3.1 Deciding which files should be preserved

Unlike many other types of data, large volumes of data are created for a photogrammetry project. Data submitted for archiving will consist of at least a set of photographs with associated metadata. In addition to the photographs, there may be camera calibration data, matrices of various kinds, coordinates, files capturing different stages of the photogrammetry flow and a project file with the finished model.

3.2 Deciding how it should be preserved

Typically, photogrammetry applications collect all related data in a project file. The project file may contain a list of all uploaded photographs, the layers and masks that have been applied to the photographs, information about the location of the camera(s) relative to the object photographed, compact point clouds, mesh models (with any manual settings by the user) and texture reconstructions (Bennett 2015). Photogrammetric project files are often in proprietary[6] format and are not suitable for archiving. If the application has an export function, it is a good idea to convert the data to the appropriate archive formats in the application in which it was originally created. If this is not possible, for example if the desired format is not supported by the original software, the data may need to be converted to an intermediate format which can then be converted to the target format using additional software. It is advisable to archive point clouds and unfinished mesh models, among other things, as separate files, as this provides better conditions for reuse in the future.

Significant properties

When deciding which files to use for archiving, it is recommended that one choose a format that preserves significant properties of the file, and that the format should be commonly used. Common file formats can usually be opened in several different applications, which increases the chances that the file format will be readable in the future. As with some other data types, text-based file formats are the most stable formats for archiving of 3D photogrammetric data. The data creator should, if possible, choose open, well-documented formats that allow access to data independently of specific applications.

Since photogrammetry does not involve a single file with a specific set of properties, here is a list of data that should be submitted for archiving.

- **Photographs** – Applies to both original images and images that have been processed in some way for use in photogrammetry.
- **Point clouds** – Since point clouds can be processed and reused, a file with the point cloud should also be submitted for archiving.
- **Calibration images** – If the camera's internal parameters have been calibrated, calibration images and associated metadata should be submitted for archiving.
- **Reference and other matrix information** – Where the photogrammetry model has spatial reference information, coordinates, control points and other documentation need to be preserved.

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[6] Proprietary file formats are file formats that have restrictions (usually set by the owner) on how they can be used, modified, or copied.

- **The finished 3D model, with or without texture information** – This is not necessary, but since the mesh model can be said to represent the finished three-dimensional reconstruction, it is desirable that this is also preserved. Preferably with the texture from the photographs.

For photogrammetry data to be reusable, at least the photographs need to be submitted for archiving. Other data types are also useful, but the photographs are a prerequisite for generating a completely new model. It is also desirable for point clouds to be submitted for archiving because it saves time and simplifies the process of re-generating the model. Given the rapid development of 3D software, it is recommended that all basic source data, which has been gradually built up during the project, be preserved for use and editing in future applications (Bennett 2015). The project file with the finished model may also be submitted for archiving, but in this case, you should find out whether the data can be accessed via the project file. Often the project file links to data stored elsewhere and if the path is not correct, the data will not be accessible. In such situations, the project file serves no purpose for a secondary user.

Recommended file formats

Many available file formats are proprietary. As a result, the data creator cannot always choose file format, and must use one of the formats of the application being used. This can make migrations between different formats difficult. For most 3D models (including those not created by photogrammetry), the OBJ and PLY formats are the best at preserving the geometries and visual surface properties of 3D objects, but they are not suitable for more complex scenes requiring light sources, or complex interactivity.

The file formats described below are those recommended for the preservation of photogrammetric data (not applicable to raster images):

Format	Description
AutoCAD DXF (.dxf)	Only suitable for dissemination and archiving if the data was originally created in CAD. The ASCII version of the format is preferred for preservation.
COLLADA (.dae)	Suitable for the dissemination and archiving of mesh models, but only recommended where the X3D format is not available.
CSV (.txt, .csv)	Suitable for the dissemination and archiving of point clouds.
Stanford PLY (.ply)	Suitable for the dissemination and archiving of point clouds and mesh models, but only recommended where the X3D format is not available. The ASCII version of the format is preferred for preservation.
Universal 3D Format (.u3d)	Suitable for archiving mesh models, but only recommended where the X3D format is not available.

VRML (.vrml)	Suitable for archiving mesh models, but only recommended where the X3D format is not available.
X3D (.x3d)	Recommended for the dissemination and archiving of point clouds and mesh models.
Wavefront OBJ (.obj)	Suitable for the dissemination and archiving of point clouds and mesh models. The ASCII version of the format is preferred for preservation.

3.3 Metadata and documentation

In addition to metadata describing the project itself (for example, contact details of the project manager, a link to a website, copyright information, etc.), data needs to be sent with metadata related to the photographs, to the camera, to the finished model, etc.

The level of detail required to fully document the entire workflow varies depending on the purpose of the project, the complexity of the end product and the technology used to generate the finished result. Some file formats allow some metadata to be stored in the file itself, but make sure that metadata is also stored separately and deposited in a separate file so that elements in the finished product can be checked against the file's contents.

The metadata elements listed below mainly describe technical data.

Image metadata

It is recommended that the photographs used in the photogrammetry project are accompanied by at least two categories of metadata: 1) image metadata and 2) camera metadata.

Properties	Description
For each set of images	
Project name	Title of the project and any abbreviation or alternative title.
Number of images	The total number of images submitted for preservation.
Camera specifications	Make and model of the camera and lens used.
File name for planimetric sketch or map	File name and file extension. Should include a description of the object and other surrounding objects (if any), the position and orientation of each image, and additional comments and/or observations.
Camera calibration file	For details on camera calibration, see the section *Camera metadata - Camera calibration*.

Supplementary notes	Any supplementary notes that may be useful to a secondary user.
For each individual image	
Image file name	File name and file extension.
Description of location and orientation	Should describe the location in general terms and the relationship of the camera to the object (for example, 'the camera is facing south').
Format conversions (if any have been done)	List of any changes to the format of the digital images and information on the software used.

Camera metadata

Camera calibration

For projects with high accuracy requirements, camera calibration is necessary. The tables below list the metadata that applies to camera calibration, including documentation of the camera's internal parameters.

Properties	Description
Date of calibration	The date on which the calibration was performed.
File name, camera calibration file	The exact name of the camera calibration file.
Camera specifications	Make and model of the camera and lens used.
Image sensor size in pixels[7]	Width and height of image sensors, measured in pixels.
Image sensor size in millimetres	Width and height of image sensors, measured in millimetres.

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[7] The size of the individual pixels and the resolution of the image sensor largely determine the image quality. Generally speaking, a larger pixel collects more light and produces less noise in the image than a smaller pixel. Especially in low light, a larger pixel size is therefore advantageous. The number of pixels in an image sensor determines the resolution of the image. The size of the individual pixels and the number of pixels determine the size of the image sensor.

Focal length and principal point[8]	The exact focal length (or focal distance), the position of the principal point and how this is measured during camera calibration.
Lens distortions (parameters K1, K2, K3, P1 and P2)	Radial and decentred distortion parameters measured during camera calibration. Given as: K1, K2, K3, P1 and P2.
Affine distortion	Affine distortion parameters measured during camera calibration (if this is done).
Quality values	Quality values such as overall RMS[9], maximum residual[10] and photo coverage[11] (given in %) from the calibration process.
Calibration adjustment information list	A report/list of information about the quality of the camera calibration, including the correlation between external and internal parameters.

Calibration images

Properties	Description
Names of image files	File names of calibration image files.
Description of the calibration target	Includes dimensions of the target, the creator, and a description.

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[8] Principal point refers to the point at which the optical axis intersects the principal plane. The principal plane is perpendicular to the axis of a lens.

[9] Root mean square (RMS) value for granularity.

[10] *Residual* is the error value in pixels between where a point is marked (either by the user, or automatically) on a 2D image and where the 3D point associated with the marked point ends up in comparisons with the 2D image. *Maximum residual* is the maximum error value for all selected points in the project. A project with high quality requirements should normally have a maximum residual value below 1.0 pixel (although there are exceptions where a higher value may be acceptable).

[11] The extent to which an area is covered by the photographs in a series of images.

Metadata for reference systems

If geographical reference information is included in the project, metadata needs to be provided for the control points.

Properties	Description
For each control point	
Equipment and reference systems	Indicate the source (for example total station or GPS and WGS84, UTM, LRF) for the collection of control points and the current reference system. The make and model of the equipment used should also be specified.
XYZ coordinates	List the three-dimensional coordinates of each control point.
XYZ covariance matrix	If a covariance matrix is available, full correlation is given, otherwise the calculated standard deviation or variance for each coordinate is given.
Description of the location	Provide a brief free text description of the location of each control point.
An image of the location of the control point	An image that clearly shows the location of the control point in relation to other known phenomena.
Geometric constraints[12] for reference information	List all known geometric constraints (if any).
Coordinate system	Name of coordinate system, reference system and projection.

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[12] Geometric constraints means that image matching problems are solved by limiting the volume of possible solutions.

Model metadata

If the images are processed with photogrammetry software and this results in a 3D model (including point clouds and 3D mesh models) to be archived, metadata in accordance with these file types should also be included. The following items can be entered individually or described in a text file.

Properties	Description
Name and version of software	Includes full details of the software name, manufacturer and version used.
RMSE values[13]	Root mean square error (RMSE). Specify the standard deviation of measured control points.
Constraints on object points	List of constraints used during processing.
For each point:	
Type of point	Node,[14] control point, or checkpoint.
Covariance matrix a priori	Enter the covariance matrix (if available) for points before merging images.
Image coordinates and error values (residuals)	A list of the images in which a point is included. For each image, coordinates and error values are given.
XYZ before and after	XYZ coordinates before and after bundle adjustments.[15] Applies to control points and checkpoints.
For each image:	
External orientation	List external orientation parameters for each image.

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[13] RMSE is a measure of the spread of the deviations, for example when a comparison is made against a given value, or as a measure of the mean of the standard deviations or standard errors.

[14] The node is a point that has no known ground coordinates but can be recognized visually in the overlap area between two or more images.

[15] https://en.wikipedia.org/wiki/Bundle_adjustment. Accessed 16 August 2022.

4. File format

When photogrammetric data is to be archived, the original photographs should be stored with the other data. There are several file formats suitable for archiving raster images, but these will not be listed here. See instead ARIANDE's guide *Raster images: a guide to good practice*, which provides information on what to consider when future-proofing raster images and which formats it is appropriate to use.

The tables describe some common file formats for photogrammetric data and which of these are recommended for archiving. Some of these formats may appear obsolete, but they are described here because it may be necessary to handle older file formats:

AutoCAD DXF	
File format/ extension	DXF/.dxf
Format	Autodesk Drawing Interchange Format (DXF) is a CAD data format developed by Autodesk to enable the transfer of data between AutoCAD and other applications.
Description	Autodesk DXF format is primarily a CAD transfer format and is compatible between CAD and GIS, among others. Few applications support the format. DXF should only be used for 3D content created using CAD software. DXF has undergone many revisions and updates since it was first developed in 1982 and its format capacity has evolved over time. The format can be used for some data in a photogrammetry project.
Recommendations	Only suitable for dissemination and archiving if (photogrammetry) data was originally created in CAD. The ASCII format is preferred for preservation.

Autodesk FBX asset exchange format	
File format/ extension	FBX/.fbx
Format	FBX (formerly **F**ilm**box**) is a proprietary file format developed by Kaydara and owned by Autodesk since 2006.
Description	FBX is one of the most popular and widely used 3D file formats and handles both 2D and 3D. The format supports geometry, colour, texture, and animation, among other things. FBX is common among film and game developers. The format is supported by most 3D applications and can be converted to .obj, .dxf, .3ds and .dae, among others. FBX is available as both a binary and an ASCII-based version. No official specification for the format has ever been published. FBX is an interchange format.

Recommendations	Works for the dissemination of mesh models but is only recommended if the ASCII version is selected and where the X3D format is not available.

COLLADA

File format/extension	COLLADA[16]/.dae
Format	COLLADA (COLLaborative Design Activity) was developed by the non-profit Khronos Group consortium and is an ISO standard (ISO 17506:2022[17]).
Description	COLLADA is an open XML-based format designed to serve as an interchange format for complex 3D data. The format supports non-destructive compression and can be used as an interchange format without risking loss of information. COLLADA supports geometry (B-rep[18]), animation, realistic physics and shading and is therefore a format suitable for storing finished photogrammetry models.
Recommendations	Suitable for the dissemination and archiving of mesh models, but only recommended where the X3D format is not available (see later in the document).

CSV

File format/extension	CSV/.txt, .csv
Format	CSV (Comma-separated values) is a general, common format that stores tabular data (numbers and text) in plain text.
Description	CSV is a text file format used to store text information in an ASCII database table. Text files can store data in a database table where the contents of the cells are separated by a delimiter such as a comma, semicolon, space, tab, and vertical bar (|). CSV can be used to transfer data between applications that have different file format standards. CSV lacks a specification, and it is easy to find differences between different CSV formats. The software, system and local settings affect what the CSV export of a database or spreadsheet will look like.

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[16] https://www.khronos.org/collada/. Accessed 25 August 2022.
[17] https://www.iso.org/standard/78834.html. Accessed 25 August 2022.
[18] B-rep models generate 3D objects by describing the various subdivided boundary surfaces of the object. B-rep models can generate complex objects, but as a result the data structure may be memory intensive.

Recommendations	Suitable for the dissemination and archiving of point clouds.

PDF/A (3D PDF)

File format/ extension	PDF/A-1 /.pdf-1a
Format	PDF (Portable Document Format), created by Adobe, is essentially an open standard for transfer between systems. The format comes in several variants, including PDF/A-1.
Description	Although PDF/A-1 is a proprietary binary format, it works well for disseminating material as it is designed to maintain the format of the original document. In addition to displaying plain text, the format can contain a wide variety of embedded file formats or linked media, including raster and vector graphics, JavaScript, and 3D objects. PDF files can be protected so that it is not possible to edit or print the document. For 3D data there are a large number of constraints. PDF/A-1 can only be used to display finished 3D models and the format does not allow a secondary user to process 3D data (for example only point clouds).
Recommendations	PDF/A-1 has been accepted as a viable format for archiving (for example by the Library of Congress[19] and the Swedish National Archives). The format is not suitable for archiving 3D models, but depending on the purpose, it can be used for dissemination.

Stanford PLY

File format/ extension	PLY/.ply
Format	Polygon file format (PLY)[20] was developed by Greg Turk at Stanford University in the 1990s.
Description	PLY is available both as an ASCII-based format and as a binary format. PLY stores properties such as texture (for example from photographs), colour, transparency and xyz values (height, width, and depth). For complex 3D datasets and visualizations, COLLADA and X3D formats are preferred, but in most cases, PLY is an adequate format.

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[19] http://www.digitalpreservation.gov/formats/fdd/fdd000125.shtml. Accessed 25 August 2022.
[20] http://paulbourke.net/dataformats/ply/. Accessed 25 August 2022.

Recommendations	Suitable for dissemination and archiving of point clouds and mesh models, but only recommended where the X3D format is not available. The ASCII format is preferred for preservation.

Universal 3D Format (U3D)

File format/ extension	U3D/.u3d
Format	U3D was developed by a consortium called the 3D Industry Forum and is a standard format (ECMA-363).[21]
Description	U3D is a compressed transfer format with an open specification that stores vertex-based geometry, colour, and texture, among other things. The latest version of the format also supports curved surfaces. The format is supported by most applications. PDF uses U3D to embed 3D objects in PDF files.
Recommendations	Suitable for archiving mesh models, but only recommended where the X3D format is not available.

VRML

File format/extension	VRML/.vrml
Format	VRML (Virtual Reality Modelling Language[22]) is a file format used to represent three-dimensional (3D) interactive vector graphics.
Description	VRML is a text-based standard (ISO/IEC 14772-1:1997[23]) specifically developed for the internet to represent 3D interactive vector graphics and is the predecessor of X3D. The latest version was published in 1997 as VRML 2.0/97. The format supports animations, transparency, and external light sources, among other things.
Recommendations	Suitable for archiving mesh models, but only recommended where the X3D format is not available.

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[21] http://www.ecma-international.org/publications/standards/Ecma-363.htm. Accessed 25 August 2022.
[22] http://www.web3d.org/standards. Accessed 25 August 2022.
[23] https://www.iso.org/standard/25508.html. Accessed 25 August 2022.

X3D

File format/extension	X3D/.x3d
Format	X3D is an ISO standardized (ISO/IEC 19775-1:2013[24]) XML-based format developed by the Web3D consortium.
Description	The X3D (extensible 3D graphics) format has been an ISO standard since 2006. X3D is an open format used by several 3D modelling applications with open source code. Polygonal models stored in X3D can store geometry (NURBS[25]), textures, animations, external light sources and a number of other features used for rendering. The format is suitable for storing both standalone 3D models and more complex 3D content such as virtual reality (VR). The format is similar to its predecessor VRML, but X3D is preferred. X3D has more features and is a more modern format. The format is the core of 3D in HTML5. X3D is similar to OBJ.
Recommendations	Suitable for the dissemination and archiving of point clouds and mesh models.

Wavefront OBJ

File format/extension	OBJ/.obj (.mtl, .jpg)
Format	The Wavefront OBJ file format was developed by Wavefront Technologies and is an open format that has a large user base.
Description	OBJ is an open format that stores 3D objects and is accepted by almost all CAD/photogrammetry/3D modelling applications. The format can be used for many different types of 3D object and can store files with high polygon counts and complex polygon structures. The format stores both geometry and texture and consists of an obj file (ASCII or in a binary format) with an mtl file (material and texture) and an image (the actual texture is taken from a photograph). For very complex 3D datasets and visualizations, COLLADA and X3D formats are preferred, but in most cases OBJ is an adequate format.
Recommendations	Suitable for the dissemination and archiving of point clouds and mesh models. The ASCII format is preferred for preservation.

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[24] https://www.iso.org/standard/60760.html. Accessed 25 August 2022.
[25] NURBS (Non-Uniform Rational B-Splines) geometries are determined by a number of fixed control points. The control points are either attached directly to the surface of the object, or float outside the model and behave as if they were attached to the figure with rubber bands. NURBS allows concave and convex polygons.

XYZ Point cloud

File format/extension	XYZ/.xyz
Format	XYZ is a generic file format for storing three-dimensional point clouds.
Description	There is no official specification for XYZ Point cloud. The format is available both as an ASCII-based format and as a binary format. In ASCII format, the location of each point/corner (in mesh models, the points correspond to the corners of the polygons) is presented by three columns, each column containing either x, y, or z values. There may also be additional columns with, for example, RGB information. The .xyz format may be regarded as part of a more general type of file format and there are large variations between how different XYZ files store data. Therefore, XYZ files are usually converted to other file formats, such as CSV. Few photogrammetry applications are currently capable of importing XYZ files.
Recommendations	Not suitable for dissemination and archiving.

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