

## DIGITAL PHOTOGRAMMETRY

*Seta Štubec (University of Ljubljana) & Ján Zachar (Via Magna)*

According to the basic formal theoretical definition, "photogrammetry is a science dealing with the reconstruction of shape, size and position of objects displayed on measurement photogrammetric images. Measurement image, or else the reference model, essentially forms the basis of photogrammetry as a measurement and mapping technique". It enables achieving the most precise and fastest depiction of natural and artificial objects on the Earth's surface. Under certain conditions, the measurement image can become an exact central projection of the photographed image, which means that it is a method of optic measurement. Measurements are taken on photogrammetric images or on the optic model<sup>1</sup> created from the measurement images. Based on these definitions, photogrammetry can be perceived as a separate geodetic and cartographic method. Photogrammetry follows the principle of transmitting information from the central projection to orthogonal projection using graphical, optical or mechanical and analytical tools. This means that distinct geometric relations that existed between the object and its image during the time of exposure can be reconstructed on the basis of geometric quantities depicted on the image (Bitterer 2006).

Recording of measurements on photogrammetric images or on reference models, which substitutes recording of measurements directly on the object or in the field, represents the basic specificity of photogrammetry that distinguishes it from the number of other geodetic methods. This prospect introduces significant benefits that, to a large extent, make the measurement work easier, save time and, to a certain degree, reduce costs. A considerable benefit lies also in the fact that measurement on the basis of photogrammetry is performed without direct contact with the object. Photogrammetry has found

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<sup>1</sup> <http://svf.uniza.sk/kgd/skripta/fotogrametria/kap01.pdf>.

mass application in the era of transition from analogue to digital platform, the process generally related to the advantages of digital photography as such. 'Digital photogrammetry' is currently widely applicable in many areas and scientific disciplines, especially due to its diverse potential and the fast development of digital technology. It works with digital images and mathematical models of analytical photogrammetry. In general, it can be established that digital photogrammetry provides:

- high resolution of the details measured,
- measurement of objects changing and moving at the time of imaging,
- high accuracy of measurement,
- orthophoto images and 3D models in a computer environment (Bartoš, Fraštia 2011).

It is especially the creation of orthophoto images and 3D models, which forms the focus of this publication, that is essential from the perspective of practical needs of different areas of cultural heritage.

Photogrammetry, that is, its different aspects, can be categorised according to various criteria. From the perspective of sensing position, we distinguish aerial and close-range photogrammetry.

- Aerial photogrammetry represents one of the techniques of the Earth's surface remote sensing, which also includes satellite imaging. As the name suggests, aircraft represents the basic carrier for sensing. Large- or medium-format digital camera is used as the sensor. An important piece of equipment is the navigation system, as well as the system for direct orientation of the sensor.
- Close-range photogrammetry deals with the evaluation of measurement image from fixed terrestrial positions, whereby it utilises several methods that allow obtaining spatial information about the objects depicted in the image. Thanks to its wide scope of application, it is one of the most widespread measurement techniques. It is used for making 2D and 3D documentation of objects and situations by means of non-contact measurement of their images. The accuracy and geometric resolution depend on the distance of imaging and the size of the focal length of the objective. Close-range photogrammetry works with object distances of between 0.1 m - 350 m, where both the lower and the upper end of the range are not strict.

Photogrammetry (especially close-range) can be classified, from the perspective of the methodology of collection and processing of the data, into single image photogrammetry, stereophotogrammetry, convergent photogrammetry and image-based modelling.

- Single-image photogrammetry represents the simplest method that uses one image of the given object, whereas the position is chosen to have the imaging axis approximately perpendicular to the measured object. The aim is to import the distorted image into orthogonal projection through projective transformation. This method is used for the reconstruction of planar objects; for spatial objects, additional information about the depth of the object documented is required. It is also used for measuring building facades and for the creation of photo-plans. Up until the onset of image-based modelling, this was the most frequently used photogrammetric method for documenting results of archaeological research. Basically, it is the classic 2D photogrammetry.

- Stereophotogrammetry is a multi-image photogrammetric method used for sensing spatially uneven objects or structures using stereoscopic perception. It is based on the correct identification of the same (G)CP on two or more images. In the past, this was the most efficient photogrammetric method, with benefits including high effectiveness and also the possibility of application of any photogrammetric system. Its application is presently declining, especially due to the popularity of image-based modelling.
- Convergent photogrammetry is another multi-image photogrammetric method. Camera axes are aimed approximately at the centre of the object measured, usually to have the object depicted in the largest possible area of the image, with the largest possible overlap. Methodologically, this is an alignment of the beam with the mathematical model of perspective photogrammetry. Nowadays, this method is slowly being replaced in the documentation practice by the method of image-based modelling.
- Image-based modelling is a method that is based on full automation of the process. The advantage of this method is in the fact that, instead of the time-consuming manual measurement of points on images, the required level of detail of the modelled areas can be achieved by choosing sufficient density of the point cloud. This is currently the most frequently used method due to the automation of the whole process and its reasonable price (Fraštia 2009).

## 2D PHOTOGRAMMETRY

2D photogrammetry has already become a regular element of the traditional documentation approach in archaeological excavations. In its essence, it is generally a single image photogrammetry.<sup>2</sup> Photographs are taken from above as vertically as possible using a ladder or a pole (if possible, an unmanned aviation vehicle (UAV) can also be employed). The photographs are then rectified and georeferenced using GCP measured by the total station or a GPS device. The archaeological units captured on such photographs are afterward vectorised and the result transferred into an orthophoto plan.

When taking a photograph, the analogue signal that is acquired and turned into a digital image is degraded in various ways. It has to be taken into account that geometrical distortions occur in every image because the three-dimensional (3D) properties of the scene are mapped onto a two-dimensional (2D) sensor plane. The mapping result (i.e. the final image) is influenced by a wide variety of factors, of which geometric errors induced by the optics, the tilt of the camera axis and the topographic relief contribute the most to the image deformations. Compensating for these deformations through some kind of geometric correction is essential for the extraction of accurate information by means of vectorisation. In general, there are two ways of dealing with these geometric deformations: simple rectification and rigorous orthorectification (Verhoeven et al. 2013).

### *Simple rectification*

For tilted images, the scale will vary with direction: the background of tilted photographs features a scale smaller than the scale of objects in the foreground. The projective

<sup>2</sup> The theoretical background derives from the paper Zachar & Štuhec (2015). (Case studies: the Čachtice and Bratislava castles, Slovakia). The article was prepared within the frame of the CONPRA project.

transformation of a tilted image to a horizontal plane can remove the contortions caused by the inclination (and thus scale differences). Such a procedure is called (planar) rectification and the result is a rectified photograph. Often, the first and second order polynomials are also used to obtain (semi-)rectified photographs, although these algorithms differ to a varying degree from the aforementioned projective transformation.

In the absence of lens distortions and perfect flatness of the imaged scene, the rectified tilted image will be identical to a vertical image and the result will be a true orthophotograph. However, lens distortions are always present and truly flat surfaces are seldom found at archaeological excavations. Since differences in height will cause topographic (or elevation) displacements, any feature lying above or below the horizontal reference surface will be misplaced in a planar rectification. More advanced algorithms are thus required if accurate mapping from the photographs is needed (Wolf, Dewitt 2000).

### ***Rigorous orthorectification***

When the geometric image correction aims to compensate also for topographically- induced deformations and lens distortions, this is called orthorectification or differential rectification. The result of such correction is a planimetrically correct true orthophotograph. Until a few years ago, true orthophotographs could only be achieved with advanced photogrammetric packages such as the Trimble INPHO Photogrammetric System. Besides the high cost, these packages were also of limited use in excavation documentation because the photogrammetric skills were essential. However, due to the ever-expanding technological improvements in computer hardware and the significant advances made in the past fifteen years in the scientific development of computer vision, many cost-effective approaches exist today. Additionally, they allow for a straightforward workflow and can still produce metrically accurate true orthophotographs (Verhoeven et al. 2013). One possible solution is to pre-process the photo prior to the rectification process with the help of an appropriate image correction software that would compensate for the radial and tangential distortion.<sup>3</sup>

### ***Practical approach in 2D Photogrammetry***

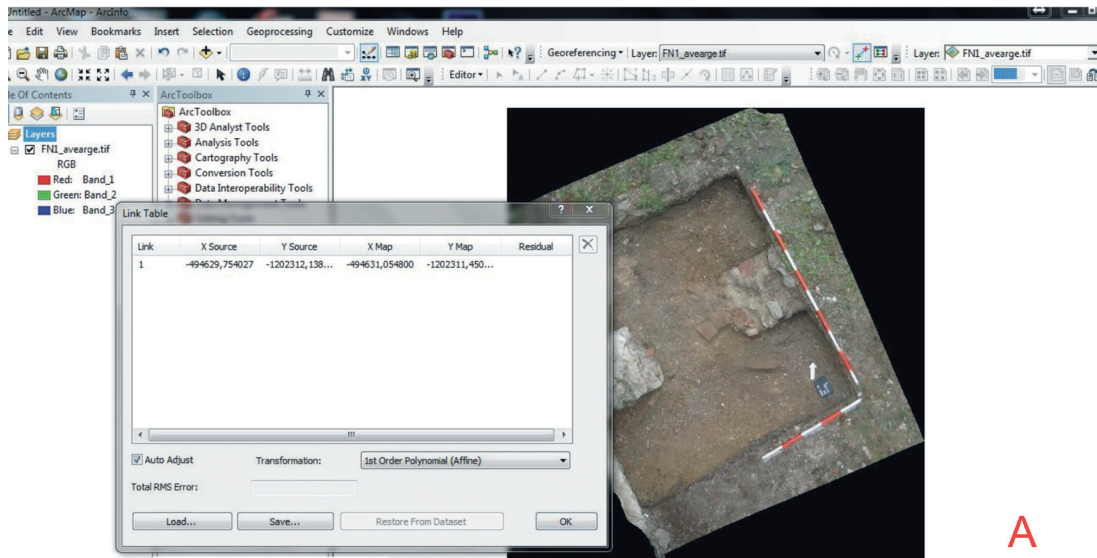
Nowadays there are plenty of tools available for photo rectification. Most commonly used are the ones implemented in CAD and GIS solutions. Autocad Civil 3D with Raster Design extension offers several rectification options. The polynomial transformation of the 1st grade usually turns out to be the most suitable choice. It is characterized by an independent scaling of x- and y-axis with no local rectification.<sup>4</sup> Beside the 1st grade polynomial transformation, this software offers polynomials of the 2nd and 3rd grade (similarly to the ArcGIS georeferencing options) as well as the triangular rectification (Figs. 6, 7).

During the triangular rectification, GCP pairs are precisely coupled spatially, and the triangles between them are stretched and squeezed to fit by calculating the polynomial coefficient of each triangle. This is the most precise method with potential imperfections only 'inside' the triangles. The negative aspect is the fact that space outside triangles is not included in the final result (raster cropping of the convex hull). In order to check the accuracy, the root mean square error (RMS) is calculated. CAD software Microstation enables orthorectification procedure via warping options.

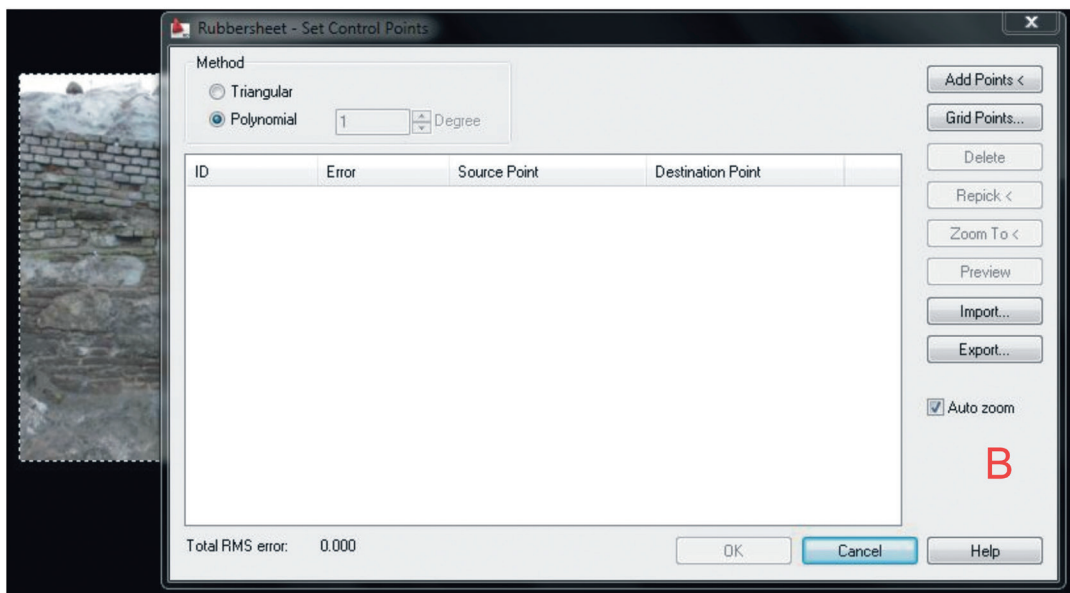
<sup>3</sup> It is possible to use software that comes with the camera, or DxO Optics Pro, which compensates for the lens distortion by using appropriate camera optics module.

<sup>4</sup> In the software-related terminology this procedure is referred to as 'rubbersheeting'.

As already mentioned above, the basic problem facing 2D photogrammetry is the insufficient tangential and radial lens distortion correction, which causes insufficient correlation of the plans of the captured scene characterised by great differences in height. This causes serious problems in the usage of 2D photogrammetry for documenting masonry structures that have a significant height distinction between the top and the bottom parts of the walls.



A



B

Figure 6. 2D Photogrammetry, orthorectification procedure.  
A: ArcMap interface, B: Autodesk Civil 3D + Raster Design interface.

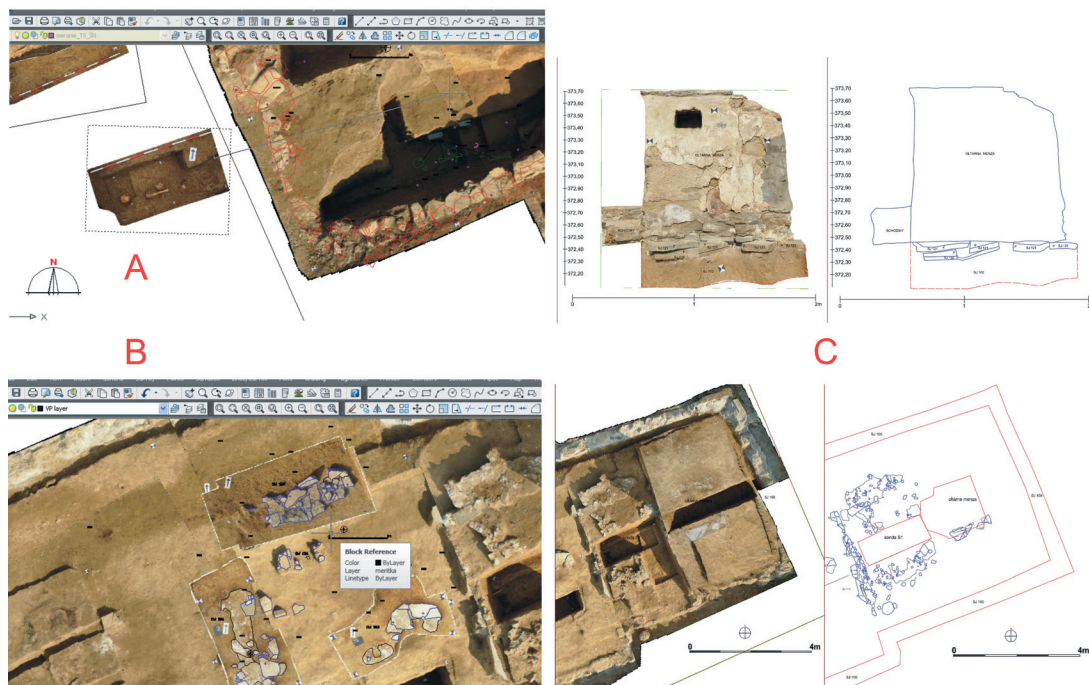


Figure 7. 2D Photogrammetry, basic workflow. A: georeferencing a photogram according to the measured ground control points (orthorectification), B: vectorisation of a photogram, C: print layout.

## IMAGE BASED MODELLING (IBM)

Image-based modelling (abbreviated as IbM) represents an algorithmic extension of stereophotogrammetry, especially in the sense of process automation. The algorithmic basis of IbM is the image correlation of input data (image rasters) that substitutes the natural stereoscopic view. Such correlation subsequently automatically generates a point cloud of a certain density, which forms the frame of the future model. Image correlation (Figure 8) analyses the similarity and the possible match between the two data files. It is, basically, an assessment of the correspondence between image parts on two or more images. It concerns comparison of the pixel surroundings on the first image, the so-called reference comparison matrix, with the surroundings that at least approximately match the position of the other pixel on the so-called searching matrix. It results in the calculation of a correlation coefficient in each of the compared positions. The coefficient can range from 0 to 1, i.e. it can signal absence of any match between the matrices (0) or indicate a match (1). If the correlation coefficient reaches the maximum value, image coordinates of the pixel (image elements) can be used for the calculation of the spatial position of a given point (Maliariková 2011), whereby the mentioned point cloud is created as the basis of the 3D mesh.

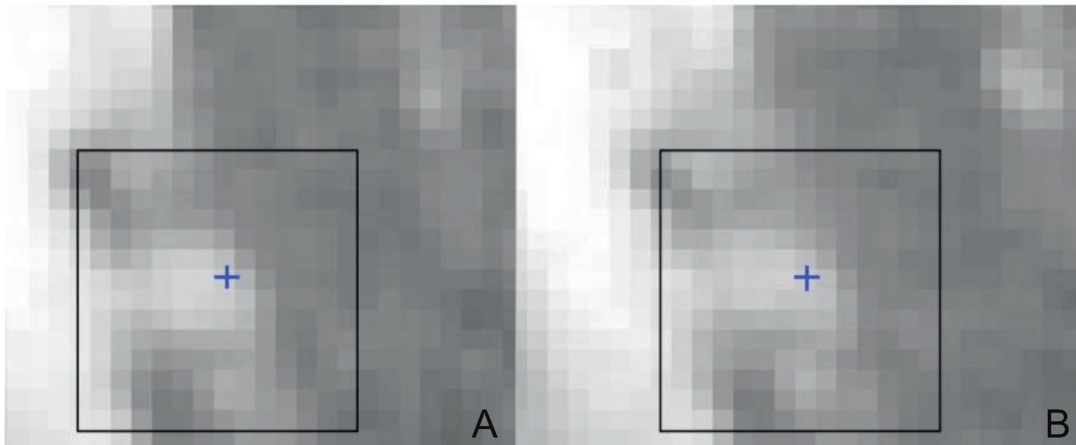


Figure 8. The principle of optical correlation.  
A: reference matrix, B: searching matrix. (Maliariková 2011, Figure 5).

As pointed above, using Ibm techniques makes it possible to calculate the 3D location of points recognizable in two or more photographs. In order to do this, the exact external (camera position and orientation) and internal camera parameters (focal length, lens distortion coefficients, principal point) have to be obtained. This can be achieved automatically using mathematical techniques from the field of computer vision called Structure from Motion (SfM). By using these algorithms, the essential external and internal camera parameters are extracted, therefore the preliminary camera calibration is not needed. The first step of the SfM approach is to search for the image-specific feature points – the so-called ‘key points’ using the principle of the SIFT algorithm.<sup>5</sup> Using the description of the features found, the algorithm matches them across the whole set of photographs (the bundle adjustment). These matches – the so-called ‘tie points’ – are then used to create the relative projection geometry (the internal and external parameters). Some software applications enable determination of a maximum number of key points and tie points in order to speed up this registration process.<sup>6</sup>

The result of this step is a sparse point cloud (i.e. a set of points with x, y and z coordinates) that represents the object’s geometry. Sparse point cloud may in some cases contain a lot of noisy points resulting from a high re-projection error or uncertainty in the reconstruction. Most software enable correction of the re-projection error through a specific refinement process that leads to cleaning of the sparse point cloud. The refinement of sparse point clouds is a delicate and important process as it significantly determines the quality of the final mesh.<sup>7</sup>

<sup>5</sup> Scale-invariant feature transform (SIFT) is an algorithm in computer vision used to detect and describe local features in images that are independent of the changes of scale. The description of features is of a vector nature. The algorithm was published by David Lowe (1999).

<sup>6</sup> Besides speeding up the alignment, setting an upper limit value for the generation of tie points filters out the points with very high re-projection error as well. However, when setting the maximum values for key points and tie points, it is necessary to keep the ratio of 2:1. Best results are usually achievable with key points: 80,000 and tie points: 40,000 or with key points: 120,000 and tie points :60,000. Lower values are possible but may result in the loss of surface geometry.

<sup>7</sup> It is always necessary to find an optimal balance between a sharp and a noiseless sparse point cloud on one hand, and not losing too many points by cleaning process on the other hand, as this may lead to disruption of the geometry of the model.

The next step is called Multi-View Stereo (MVS) approach and is used to compute a denser point cloud. Such point cloud can afterward be turned into a mesh and used as a solid 3D model to which texture can be applied. Textured 3D model can be scaled or georeferenced according to the measured coordinates of ((G)CP) which are aligned with the markers detected manually or semi-automatically on photos in uploaded into the program. Most programs dispose of subsequently generated deliverables such as georeferenced ortho-photo plans or digital elevation models (DEM) (Figure 9).

It is important to understand the basic principles of the SfM+MVS approach in order to be aware of its capabilities and limitations. For example, the SfM+MVS approach is useless if the object lacks distinct texture, which is necessary for the recognition of feature points. Shiny or glassy objects are also more difficult to reconstruct using these methods, as their highlights are constantly changing. The best result can, therefore, be achieved with distinctively coloured and textured objects. Finally, the correct photo capture procedure is essential to achieve the best possible results.

### ***Software and on-line services***

The recent boom in computer vision programs that combine SfM approach with dense MVS algorithms makes the calculation of 3D data from photographs accessible to non-professionals. Because of their straightforward workflow and a moderate cost, these SfM+MVS software packages do not require extensive photogrammetric and computer vision knowledge of the user, nor the information on geometrical properties of the scenes. This means that no special preliminary preparation is needed (i.e. camera calibration). As such, they became a common part of the documentation practice in many research and commercial fields, including the cultural heritage monitoring and preservation.

The straightforward generation of 3D content by these SfM+MVS tools also finds useful applications in documenting archaeological excavations, for which accurate and cost-effective registration techniques are of utmost importance. Besides the advantages of these accurately scaled digital surface models in presenting the archaeological heritage, georeferenced orthophoto plans and vector drawings can also be generated from them. Today there are plenty of SfM+MVS packages available, ranging from free and open-source to commercial ones. Some of them (such as ARC3D, 123D Catch, Autodesk ReCap, Autodesk ReMake) provide an online service that automatically carries out the entire procedure. These online approaches are very easy to use. All that a user needs to do is to upload the selected images and wait to receive the 3D model. However, the number of images is quite limited and, additionally, hardly any manipulation of the parameters is possible, which represents a significant constraint in the 3D model creation.



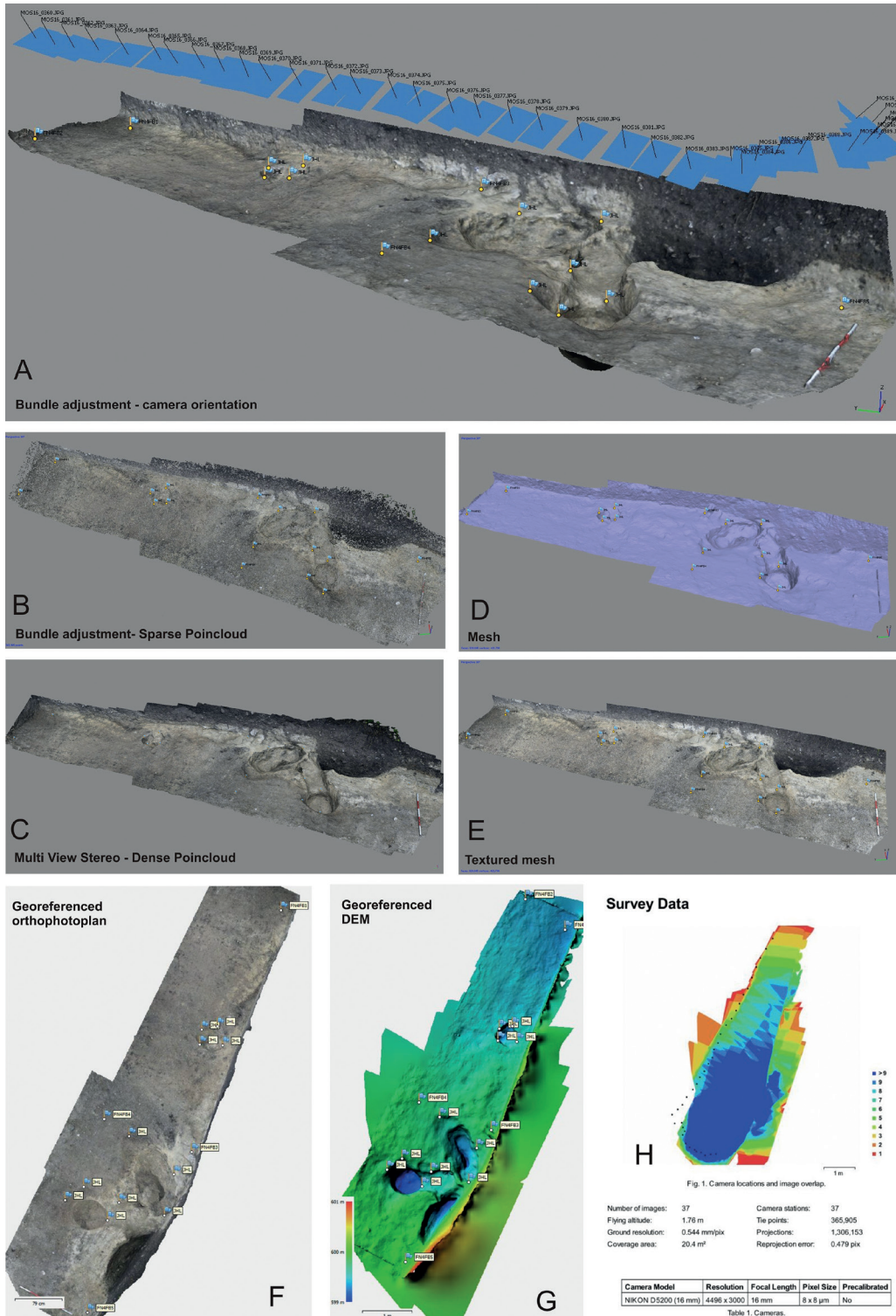


Figure 9. Structure from Motion workflow (software Agisoft Photoscan).  
 A: bundle adjustment, camera calibration – outer and inner camera orientation definition, B: bundle adjustment, sparse point cloud generation, C: Multi-View Stereo, dense point cloud generation, D: mesh creation, E: textured mesh, F: georeferenced orthophoto plan creation, G: georeferenced digital elevation model creation, H: survey data accuracy, mode resolution and quality report.

On the other hand, a computer-based software package might take a bit more time to master, but the parameters can be tailored for each specific case. Some of these programs have also additional functionalities such as scaling, georeferencing, orthophoto plans extraction, etc. which is, in the case of open-source software, rarely possible. A short list of some of the programs and online services is provided below.

Software	Web	License	Solution
Photomodeler Scanner	<a href="http://info.photomodeler.com/">http://info.photomodeler.com/</a>	commercial	desktop
Agisoft Photoscan	<a href="http://www.agisoft.com/">http://www.agisoft.com/</a>	commercial	desktop
Capturing Reality RealityCapture /RC/	<a href="https://www.capturingreality.com/">https://www.capturingreality.com/</a>	commercial	desktop
Pix 4D	<a href="https://pix4d.com/">https://pix4d.com/</a>	commercial	desktop
Acute3D ContexCapture	<a href="https://www.acute3d.com/">https://www.acute3d.com/</a>	commercial	desktop
3D Zephyr	<a href="http://www.3dflow.net/">http://www.3dflow.net/</a>	commercial	desktop
ARC3D	<a href="http://www.arc3d.be/">http://www.arc3d.be/</a>	open-source	online
Autodesk 123D CATCH	<a href="http://www.123dapp.com/catch">http://www.123dapp.com/catch</a>	open-source	online
Autodesk ReMake	<a href="https://remake.autodesk.com/">https://remake.autodesk.com/</a>	commercial	online
Autodesk ReCap	<a href="http://www.autodesk.com/products/recap-360/overview">http://www.autodesk.com/products/recap-360/overview</a>	commercial	online
University of Washington, Visual SfM	<a href="http://ccwu.me/vsfm">ccwu.me/vsfm</a>	open-source	desktop
Menci APS	<a href="http://www.menciSW.com/aps-en">http://www.menciSW.com/aps-en</a>	commercial	desktop

Table 3. Overview of the most commonly used IBM software.

### **Image-based data collection: Basic rules**

Because not a lot of metadata are needed, the above-described approach enables generation of a 3D content from almost any set of photographs. Nevertheless, in order to generate a 3D model successfully, one should follow certain rules when taking photographs on the site (Figure 10). The below listed basic principles of the photo shooting scenario refer primarily to the position and ‘movement’ of the photographer while taking the photos:

- Every photograph should be taken from a different location. If the photographs are taken from the same location, problems with alignment might occur.
- A higher amount of photographs does not necessarily mean a better result. It is, however, better to take more photographs and make a selection later. Only the feature visible on the photograph can be reconstructed, that is why it is important to capture everything.
- The photographs should be taken with a sufficient overlap. There should be at least a 60 % overlap, although 80 % often works better. A rule of thumb to follow is the ‘rule of three’, which states that each feature should be visible on at least three photographs.
- Photo sequences should be taken in a way in which the optimized mutual photo axis orientation is maintained. The angle between the axes of two adjacent photos should not exceed 25-30 degrees.

- An important element is also the image quality. Photographs should be sharp and acquired with good quality optics. If possible, it is advised to take the complete set of photographs with the same focal length and focus distance, it normally gives better results. Ibm does not set any requirements concerning the image resolution. However, it is important to remember that the resolution of the input data influences the quality of the processing results. That is why it is strongly recommended to employ a camera with at least 5Mpx resolution. If the project's objective is to produce high quality/professional orthophoto maps, it is better to opt for a minimum 24Mpx<sup>8</sup> resolution photography (sharpness is discussed in detail in the following chapter).
- Some software packages enable alignment, re-alignment and/or georeferencing using special targets – markers that come with the program and that can be calibrated. In this case, the targets should be clearly visible in the photographs (to create a texture, enough photographs without these targets should also be taken). It is possible to use non-calibrated markers as well. The size of markers should be adequate in relation to the extent of the project; the only limiting factor is that they should be visible on the photos. The distribution should be such that the markers cover the whole scene documented. In case of landscape surveys, it is advisable to measure coordinates of the markers (in this case GCP) by the total station in order to get as precise coordinates for georeferencing as possible.<sup>9</sup>
- SfM algorithm estimates the camera calibration parameters automatically; consequently, there is no need to run a pre-calibration procedure manually. However, since the algorithm in most software applies the Brown model to simulate lens assembly, automatic calibration works perfectly well only for 'standard' optics (that is, with 50 mm focal length (35 mm film equivalent)). Otherwise, if the source data is captured with a 'fish eye' or ultra-wide angle lenses, the operation is likely to fail. If this is the case, one should enter calibration data into the program for good results of the reconstruction.
- The final result of 3D Ibm can be strongly influenced by the lighting conditions. Best results are usually achieved under coherent natural diffuse lighting, which is generally guaranteed in cloudy weather.

As already mentioned, each part of the scene that is to be reconstructed in 3D should be visible on at least 3 photos. This may be a problem when documenting architectural structures. In this case, taking photos just from the ground level causes 'digital shadows' in upper parts of the architecture. The best way to avoid this is the application of pole aerial photography or unmanned aerial vehicles (UAV) to reach parts of the structure that are not accessible from the ground level. Nowadays, especially UAVs (mostly micro-copters) are becoming a regular part of the data acquisition in Ibm as they can fly in an autonomous mode using integrated GPS/INS, a stabilizer platform and digital cameras (or even a small range sensor), and which can be used to get data from otherwise hardly accessible areas.

<sup>8</sup> On the other hand, the choice of camera should not depend only on the resolution. The optics, in combination with the camera sensor, is crucial for a good photo quality.

<sup>9</sup> As for the number of GCP, it depends on the scale of the project. The basic rule is that they should build up representative information on the measurements.

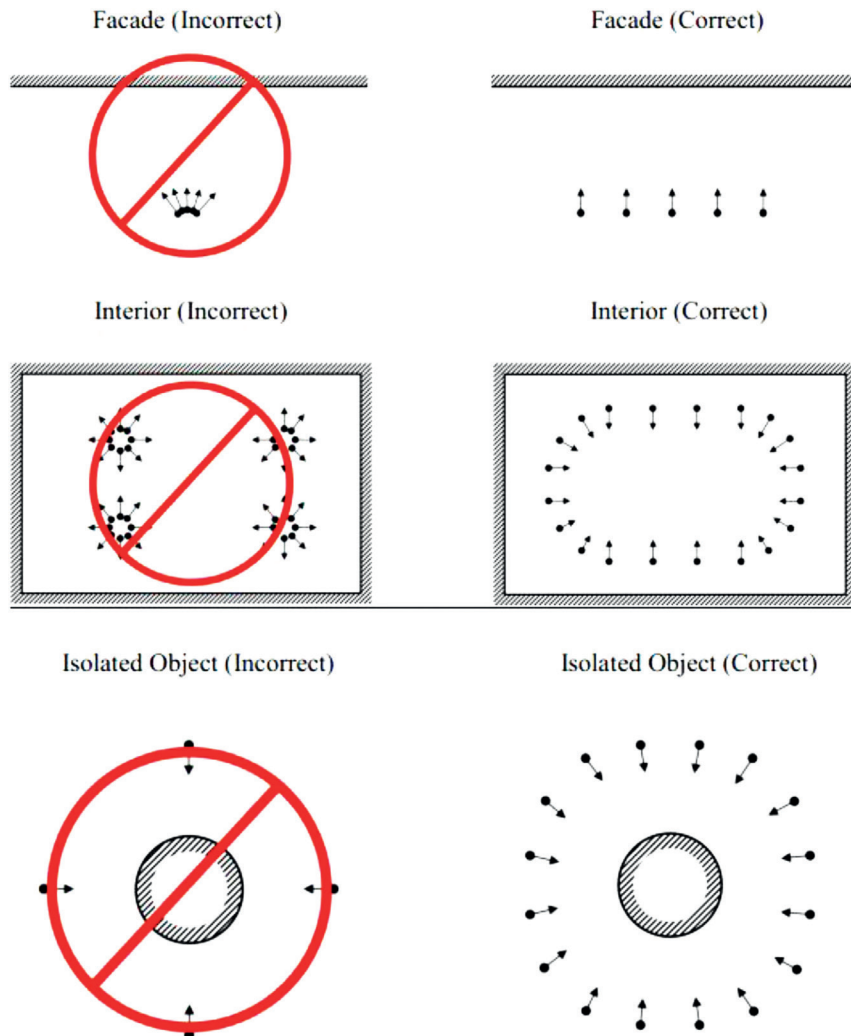


Figure 10. Photo shooting strategies for Image-based Modelling (IbM).  
 (Available online at [http://www.agisoft.com/pdf/tips\\_and\\_tricks/Image%20Capture%20Tips%20-%20Equipment%20and%20Shooting%20Scenarios.pdf](http://www.agisoft.com/pdf/tips_and_tricks/Image%20Capture%20Tips%20-%20Equipment%20and%20Shooting%20Scenarios.pdf)).

Concerning the 'terrestrial' photo shooting scenario, there are, from the practical point of view, two basic methods:

- *The walk-around method* is mainly used for documenting objects outdoors. The method entails that a photographer moves around the object following the above-mentioned rules. In case this method is used for recording of a solitary object in an indoor environment, it is necessary to do appropriate camera settings with regard to the indoor lighting conditions (see the following chapter). Photo acquisition is done via several 360 degrees photo-shooting rings, with approximately 30-50 photos per ring, depending on the size of the object.
- *The turntable method* is, on the other hand, based on photo-shooting in a single direction, from a camera mounted on a tripod. The motion is obtained by changing the position of the object photographed. In most cases, the object is placed on a base that rotates (either operated manually, or automatically by an electronic device) while

the camera is taking pictures.<sup>10</sup> Of course, the general position of the object has to be changed manually several times during photo-shooting in order to capture all possible sides of the object. In this scenario, precise light settings are essential in order to achieve good diffuse global light. Putting the object in front of a monochrome background is a good option as well, and it can help substantially in subsequent processing by generating a clear mesh with as little noise as possible (Figure 11). This shooting method is meant exclusively for portable object documentation created in internal environment.

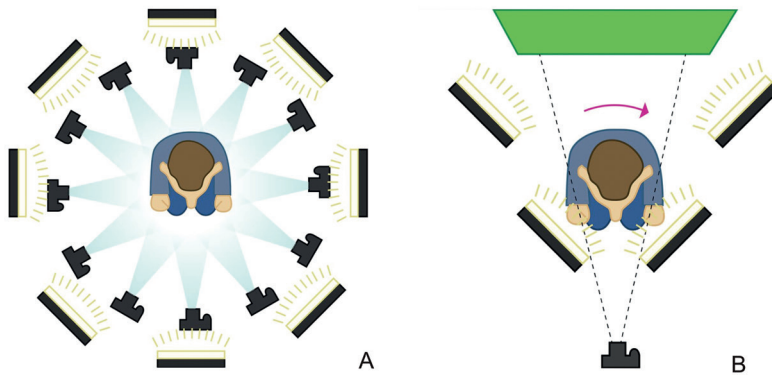


Figure 11. Photo-shooting scenario of a solitary object. A: walk-around method, B: turntable method. (Available online at <http://www.tested.com/art/makers/460142-art-photogrammetry-how-take-your-photos/>).

### ***Pre-processing the data (taking and editing photos)***

The basic material for IbM consists of source photos. As already outlined in the previous chapter, the quality of the acquired photos strongly determines the quality of the final 3D model. Therefore, paying extra attention to the image quality is a key factor for successful accomplishment of the projects. Since the sufficient number of SIFT points (key points) detectable on the image is crucial for further workflow, a high resolution, high overall sharpness and a high contrast of the photo are required.

Based on the experience obtained from the case studies, the best procedure for taking photos is through the use of a standard DSLR camera with fixed lens.<sup>11</sup> Creating RAW files is preferred to creating JPGs. Although RAW files consume much more SD card memory, they definitely contain a much higher amount of data that can afterwards be processed according to particular needs. On the other hand, the processing potential of JPG files is rather limited. Photographs should be taken in aperture priority mode,<sup>12</sup> if possible with the help of a monopod or tripod stand.

The overall sharpness of the picture is of prime importance, so the aperture should be set to minimum 5.6 or higher, but should not surpass the 'sweet spot' point of the lens, since too-high aperture values introduce high light diffraction and thus additional noise and blur

<sup>10</sup> Nowadays, there are a lot of examples of fully automated turntable data acquisition procedure, where rotation of the turntable and the camera shooting system are controlled by a computer.

<sup>11</sup> Transfocal lenses are not excluded, but the best achievable results are guaranteed by the use of fixed lenses.

<sup>12</sup> Fully manual mode would, of course, be most desirable, but is usually out of question with respect to the amount of photos taken (often hundreds, or even several thousands).

into the imagery.<sup>13</sup> In order to keep the noise as low as possible, shooting at low ISO values is recommended. For the white balance correction, calibrated colour charts should be used. If shooting outdoors, the most suitable lighting condition is guaranteed by cloudy weather which generates diffuse light. If the scene or object documented are in sunlight, this can create big differences in luminance (e.g. sharp shadows) and it may be necessary to use protective shelter if possible, or create HDR photos (see below) which can be time-consuming.

Afterward, the RAW files are to be processed in specific software in order to enhance the sharpness and colour information. The following parameters should receive special attention:

- *White balance* setting enables correction of the white balance according to the calibrated colour charts or purely manually. This step is important in order to get the relevant and true colour information on the object/scene documented for the purpose of texturing of the final 3D model.
- *Exposure compensation* adjusts the global exposure of the image and thus its overall brightness/darkness.
- *Smart lighting* (available only in some software packages) optimizes the global dynamic range of the photo by unblocking shadows and/or recovering highlights.
- *(Selective) tone mapping* allows selective adjustment of the brightness of a given tonal range (highlights, midtones, shadows, blacks). This is a very important tool used to recover detail in the highlighted and the dark parts of the image, which is crucial in case of non-diffuse lighting in the photo shoot. It is usually carried out in a balanced combination with *smart lighting*.
- *ClearView/Dehaze* (available only in some software packages) enables improvement of the contrast and sharpening of the image by removing the effects of atmospheric haze or fog.
- Within the *contrast enhancement* option, *microcontrast* and *finecontrast* sub-options are usually available. Microcontrast enhances micro details or softens them, and can be used to shadow detail recovery.
- In most software, the two tools are merged together as one common tone mapping function. Within it, especially *white clipping point* and *black clipping point* options can influence the level of highlighting of small details, which is particularly useful for a textured image or when one needs to compensate for the lack of sharpness. Finecontrast enhances or softens medium-sized details. Furthermore, in most software, there is a possibility to constrain the effect of contrast on highlights, midtones (e.g. *Clarity* available in particular software) or shadows.
- For sharpening the image, the *unsharp mask* or *masked sharpening* is the most important tool. The tool adjusts the intensity, which determines the level of sharpening of the whole image. *Radius* sets the thickness of the sharpened edges. The *threshold* is a masking option of the tool; it sets the level above which details will be sharpened or, in other words, masks the parts of the image that will thus not be sharpened.<sup>14</sup> Values that are too low may give sharper image but, on the other hand, amplify noise. Software masking can also be applied for determining the level of sharpening.

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13 The aperture substantially determines the depth of field (DOF). The bigger the DOF, the higher the overall sharpness of the image.

14 Some software packages use the term 'threshold' and some use the term 'masking'.

- *Chromatic aberration* decreases aberrations introduced by the lenses (i.e. colour artefact that can appear in the areas of transition between dark and bright zones). Besides the intensity, the size and purple fringing should also be set. The size adjusts the width of the fringe to be suppressed. Purple fringing removes the ‘ghost’ in the form of purple fringe that appears along high-contrast edges of the image.
- *Noise reduction* is a tool included in all image processing software, but equipped with different levels of strength. In most cases, *luminance* (reduces fine grain) and *chrominance* (reduces colour artefacts) noise reduction options are offered separately.

In some cases, it is necessary to augment the curvature and plasticity of a structure to the level that lies far beyond the power of the above-mentioned tools. This may be required when documenting walls covered with fine, monochromatic plaster. Such structures display very low colour differentiation and curvature, which hampers SIFT point creation. In such a situation, HDR (High Dynamic Range) approach is required, which is able to enhance even very small variations in curvature and colour hue. HDR can be generated in special software by processing at least three exposure-bracketed photos, or within single RAW photo through the application of HDR filtering. In the first case, the procedure is based on the fusion of exposure of several photos taken with different exposure values<sup>15</sup> and from the same position. In the second case, the procedure is based on the fusion of exposure values of the RAW file generated in a specific photo-editing software.<sup>16</sup> The key goal of HDR photography is to maintain stability by taking bracketed photos in order to avoid blurring during processing.

Software	Web	License	Platform PC=Windows Mac=Mac OS
Adobe Photoshop Camera RAW	<a href="http://www.adobe.com/products/photoshop.html">http://www.adobe.com/products/photoshop.html</a>	commercial	PC, Mac
DxO Optics Pro	<a href="http://www.dxo.com/us/photography/photo-SW/dxo-opticspro">http://www.dxo.com/us/photography/photo-SW/dxo-opticspro</a>	commercial	PC, Mac
Adobe Lightroom CC	<a href="http://www.adobe.com/sk/products/photoshop-lightroom.html">http://www.adobe.com/sk/products/photoshop-lightroom.html</a>	commercial	PC, Mac
ACDSee Ultimate	<a href="http://www.acdsee.com/en/products/acd-see-ultimate">http://www.acdsee.com/en/products/acd-see-ultimate</a>	commercial	PC, Mac
Phase One Capture One Pro	<a href="https://www.phaseone.com/en/Products/SW/Capture-One-Pro/">https://www.phaseone.com/en/Products/SW/Capture-One-Pro/</a>	commercial	PC, Mac
Apple Photos	<a href="http://www.apple.com/macos/photos/">http://www.apple.com/macos/photos/</a>	open-source	Mac
Serif Affinity Photo	<a href="https://affinity.serif.com/en-gb/photo/">https://affinity.serif.com/en-gb/photo/</a>	commercial	Mac
ON1 Photo 10	<a href="https://www.on1.com/products/photo10/">https://www.on1.com/products/photo10/</a>	commercial	PC, Mac
MacPhun Creative Kit	<a href="https://macphun.com/creativekit">https://macphun.com/creativekit</a>	commercial	Mac
RAWTherapee	<a href="http://RAWtherapee.com">http://RAWtherapee.com</a>	open-source	PC, Mac, Linux
1. Picasa	<a href="http://www.picasa.google.com">www.picasa.google.com</a>		PC, Mac
2. GIMP	<a href="http://www.gimp.org">www.gimp.org</a>	open-source	PC, Mac, Linux
3. Paint.NET	<a href="http://www.getpaint.net">www.getpaint.net</a>		PC

Table 4. Overview of the most commonly used RAW file editing software.<sup>17</sup>

15 At least 3 photos should be taken, preferably with the help of tripod: one photo with custom exposure, one underexposed and one overexposed.

16 Most of the currently available photo-editing software enable generation of several exposure values in one RAW file.

17 In case of open-source software, there can be limitations in the readability of particular RAW files, and some of the editing tools mentioned in the text may be missing.

Software	Web	License	Platform PC=Windows Mac=Mac OS
Aurora HDR	<a href="http://aurorahdr.com">http://aurorahdr.com</a>	commercial	Mac
EasyHDR	<a href="http://www.easyhdr.com">http://www.easyhdr.com</a>	commercial	PC, Mac
Photomatix Pro	<a href="http://www.hdrsoft.com">http://www.hdrsoft.com</a>	commercial	PC, Mac
HDR Projects 4	<a href="http://www.projects-SW.com">http://www.projects-SW.com</a>	commercial	PC, Mac
Oloneo HDR	<a href="http://www.oloneo.com">http://www.oloneo.com</a>	commercial	PC
SNS-HDR	<a href="http://www.sns-hdr.com">http://www.sns-hdr.com</a>	commercial	PC
Machinery HDR	<a href="http://www.machineryhdr.com/">http://www.machineryhdr.com/</a>	commercial	PC
Dynamic Photo HDR 5	<a href="http://www.mediachance.com">http://www.mediachance.com</a>	commercial	PC, Mac
HDR Expose	<a href="http://pinnacleimaging.com">http://pinnacleimaging.com</a>	commercial	PC, Mac
HDR Efex Pro	<a href="http://www.google.com/nikcollection">http://www.google.com/nikcollection</a>	commercial	PC, Mac
Luminance HDR	<a href="http://qtpfsgui.sourceforge.net">http://qtpfsgui.sourceforge.net</a>	open-source	PC, Mac
Picturenaut	<a href="http://www.hdrlabs.com">http://www.hdrlabs.com</a>	open-source	PC, Mac
Fusion HDR	<a href="http://fusion-hdr.com">http://fusion-hdr.com</a>	commercial	PC

Table 5. Overview of the most commonly used HDR software.

Software	Web	License	Platform PC=Windows Mac=Mac OS
Adobe Photoshop	<a href="http://www.adobe.com/products/photoshop.html">http://www.adobe.com/products/photoshop.html</a>	commercial	PC, Mac
DxO Optics Pro	<a href="http://www.dxo.com/us/photography/photo-SW/dxo-opticspro">http://www.dxo.com/us/photography/photo-SW/dxo-opticspro</a>	commercial	PC, Mac
Adobe Lightroom CC	<a href="http://www.adobe.com/sk/products/photoshop-lightroom.html">http://www.adobe.com/sk/products/photoshop-lightroom.html</a>	commercial	PC, Mac
ACDSee Ultimate	<a href="http://www.acdsee.com/en/products/acdsee-ultimate">http://www.acdsee.com/en/products/acdsee-ultimate</a>	commercial	PC, Mac

Table 6. Overview of the most commonly used software enabling HDR filtering.

All the above-mentioned principles of photo shooting strategy tend to generate RAW files with the as big depth of field (DOF) as possible within the given lighting conditions. Processing RAW files should lead to the achievement of a maximum possible level of contrast without producing artificial unwanted noise. Balancing these two requirements is a key factor in mastering the processing procedure (Figs. 12, 13).

After processing the RAW files, it is necessary to save it in common readable file, either JPG, PNG or TIFF. The best solution is to opt for TIFF file, which can contain former uncompressed photo resolution.



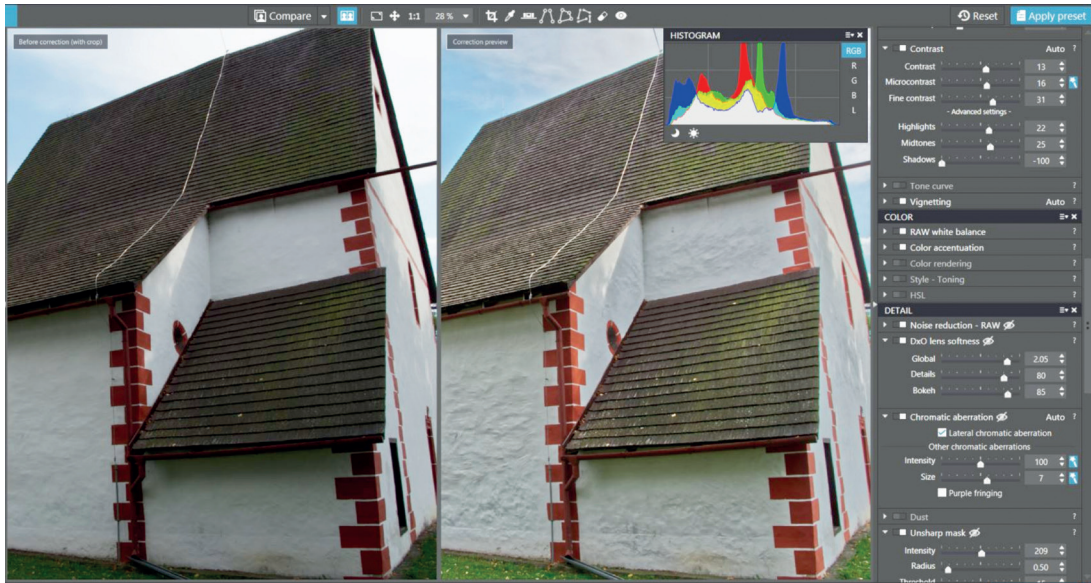


Figure 12. Processing RAW files. An example of an image before and after correction. DxO Optics Pro interface.

### **Data processing and post-processing: software applications**

Every software package has its own characteristics. Nevertheless, there are several basic rules that apply to all software solutions. In the first step, all edited photographs prepared to be processed should be finally checked for sharpness and image quality artefacts (e.g. hot pixels or bending) and in the case of poor quality, they should be eliminated. Most software enables this through the native procedure.

After loading photos to working directory or working interface, it is always desirable to check for camera calibration parameters. Most software use automatic calibration procedure according to available EXIF data of particular photos. Refinement of calibration is done through alignment of photos when the inner camera (principal point, radial, and tangential lens distortion coefficient), as well as outer camera orientation (position of the camera in space), is calculated. In the case of wide angle lenses or the absence of EXIF data whole calibration information should be done manually according to the particular workflow of a given software. Masking photos is an optional step. It is used to eliminate the background or other features that might cause alignment errors (e.g. the wind can cause some movement in the background which may disable the alignment). However, background features are usually useful for the alignment. Masking itself can be done either in a native IBM software or in a third-party software<sup>18</sup> (e.g. in Adobe Photoshop) and imported as an alpha channel.

Distribution of sparse point cloud as a product of photos alignment step can be refined through optimization of re-projection error parameters<sup>19</sup> as well as through ((G)CP) with exact coordinates measured either by total station or differential GPS GNSS RTK rover.

18 Masking may be very useful when digitising portable artefacts, e.g. a museum collection. In this case, it is usually necessary to outline sharply the edges of an artefact against the background.

19 It is reasonable to achieve a RMS re-projection error of under 1px. The refinement procedure should be carried out carefully in order not to delete too many points by lowering the mean re-projection error value as this may disrupt coherency of the whole alignment.

Measured data are put into adequate markers detected or manually created on particular photos. Via (G)CP application and the correct coordinate reference system assignment, the global georeferencing and scaling of the scene is carried out. If no coordinates are known but some distance values are available, these can be used for scaling the scene by markers as well. The final step includes dense cloud generation and subsequent meshing and texturing. The whole process is done via software's native algorithm. Most software usually enable basic editing of the mesh and texture (above all decimation<sup>20</sup>). It is however highly recommended to perform mesh editing in third party software.

Post processing strategy can be divided with reference to demands on the final output of the project. It can be 2D vector output, 2.5D digital elevation data (DEM) or fully 3D solid model. In the first two cases, 3D data are used as a mean for the extraction of 2D/2.5D data. Most lbM software offer additional functionalities such as scaling, georeferencing, georeferenced orthophoto plans and DEM extraction, which can be done in an easy straightforward manner. Once setting appropriate coordinate system and subsequent assignment of measured GCP to model or photos in lbM native software, georeferenced orthophoto plans with word file as well as georeferenced GeoTiff containing DEM are automatically exported with the given parameters (mainly resolution). These data can be subsequently put into GIS or CAD software for further processing (vectorisation, cross section generation) or visualisation. DEM creation is widely applicable in landscape survey while georeferenced orthophoto plans and their CAD vectorisation are broadly used in architectural and archaeological documentation.

In case that final output is a solid 3D model either in mesh or NURBS form, it is necessary to edit mesh in external software. The main aspects of such editing are cleaning, denoising, simplification in sense of decimation<sup>21</sup>, holes filling and finally retopologisation. Mesh retopology is usually a quite sophisticated procedure that is carried out by professionals. Its basic goal is to achieve selective simplification of the mesh while maintaining all the necessary details. Optionally it can involve transferring the triangulated mesh into quad variant which can be more precisely converted into NURBS, it means CAD friendly file format.

Custom UV<sup>22</sup> texture map creation is very often part of retopology workflow as well. Most native lbM software generates texture parameterization which is very fragmented and thus not suitable for further editing like unwrapping or changing colour hue and saturation. Therefore, it is convenient to create UV map in special modeling software and import it back into lbM where texture information can be projected upon newly created parameterized UV map. Once a cleaned and retopologised mesh optionally converted into NURBS is created, it can be used as a source for wide range of virtual reality applications.

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20 I.e. reduction of the size of the mesh by reducing the number of triangles it contains.

21 Decimation (reduction of triangles) of the produced mesh is the crucial operation, since the mesh usually contains up to tens of millions of triangles which is difficult to deal with in any software.

22 UV is used as an alternative expression for X and Y coordinates.

Software	Web	License	Retopology	Custom UV map
Geomagic Design X	<a href="http://www.rapidform.com/products/xor/overview/">http://www.rapidform.com/products/xor/overview/</a>	commercial	yes	no
Geomagic Wrap	<a href="http://www.geomagic.com/en/products/wrap/overview">http://www.geomagic.com/en/products/wrap/overview</a>	commercial	yes	no
PolyWorks	<a href="http://www.innovmetric.com/">http://www.innovmetric.com/</a>	commercial	yes	no
ZBrush	<a href="https://pixologic.com/">https://pixologic.com/</a>	commercial	yes	yes
Autodesk Maya	<a href="www.autodesk.com/products/maya/overview">www.autodesk.com/products/maya/overview</a>	commercial	yes	yes
Autodesk 3DS Max	<a href="www.autodesk.com/products/3ds-max/overview">www.autodesk.com/products/3ds-max/overview</a>	commercial	yes	yes
Autodesk MudBox	<a href="www.autodesk.com/products/mudbox/overview">www.autodesk.com/products/mudbox/overview</a>	commercial	yes	no
MeshLab	<a href="http://meshlab.sourceforge.net/">meshlab.sourceforge.net/</a>	open-source	yes	yes <sup>49</sup>
Blender	<a href="https://www.blender.org/">https://www.blender.org/</a>	open-source	yes	yes
3D Coat	<a href="http://3dcoat.com">3dcoat.com</a>	commercial	yes	yes
Modo	<a href="https://www.thefoundry.co.uk/products/modo/">https://www.thefoundry.co.uk/products/modo/</a>	commercial	yes	yes
Instant Meshes	<a href="https://github.com/wjakob/instant-meshes">https://github.com/wjakob/instant-meshes</a>	open-source	yes	No

Table 7. Commonly used mesh editing software.

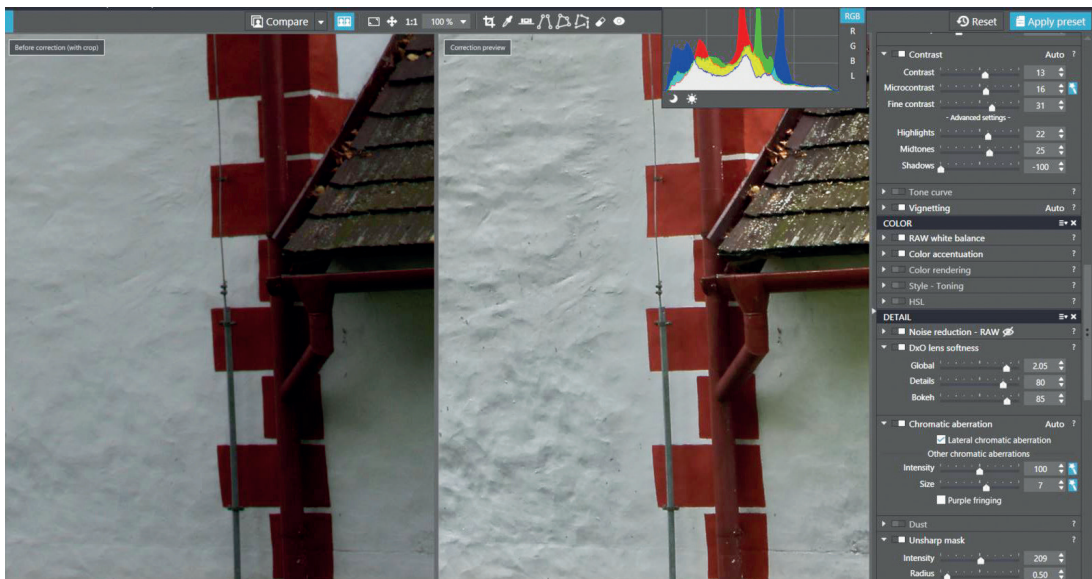


Figure 13. Processing RAW files. An example of an image before and after correction. Detail. DxO Optics Pro interface.