

DIGARCH 2015 NOTES**Structure from Motion – Multiple View Stereovision (SFM/MVS)****AN INTRODUCTION ON HOW TO PERFORM SFM/MVS**

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Abstract

The following is a compilation of informative texts related to the procedures involved when applying the *Structure from Motion – Multiple View Stereovision (SFM/MVS)* 3D digitisation approach. It focuses on issues related to the data collection phase, the methods applied in order to capture both movable (e.g. artefacts) and unmovable objects (e.g. statues, monuments, architectural, urban areas of cultural significance, etc.) and the hardware involved. It can be considered as an introduction to those interested in applying SFM/MVS successfully in the cultural heritage domain. It has been created for the needs of the Digital Technologies in Cultural Heritage and Tourism 2015 summer school and it is offered as part of the syllabus to all participants.

1. Introduction

The efficient and low-cost generation of accurate 3D digital replicas derived from the cultural heritage domain is an active and significant research area. The generation of 3D digital replicas based on *Structure from Motion* and *Multiple View Stereovision (SFM-MVS)* is evolving into a popular solution within the cultural heritage domain. Primary aspects of SFM-MVS are its cost effectiveness in terms of hardware and low background knowledge requirements. Its data collection phase is more time efficient when compared with other 3D digitization methods. The quality of SFM-MVS data composes a competent method that satisfies the requirements of a variety of digitisation projects (small movable artefacts, statues, monuments, archaeological sites and urban areas) [1].

A number of software solutions, implementing the SFM/MVS algorithms from unordered image collections have been made available to the broad public over the last years. The SFM method uses a number of unordered images that depict a static scene or an object from arbitrary viewpoints and attempts to recover camera parameters and a sparse point cloud that represents the 3D geometry of a scene. The method mainly uses the corresponding features, which are shared between different images that depict overlapping areas, to calculate the intrinsic and extrinsic parameters of the camera.

More specifically, SFM-MVS is defined as a pipeline of algorithms that are combined to create a 3D model from a set of unordered images taken from different positions, scales and under varying illumination conditions. The key parts of this pipeline are:

- (i) Feature point detection based on methods such as SIFT and SURF that identify points or regions of interest that need to be matched [2]-[5],
- (ii) Corresponding points problem that compares the SIFT and SURF output through an analysis of all the possible image combinations using either rigorous procedures such as quadratic matching or fast approximation such as the *kd-tree search* [6],
- (iii) Bundle adjustment method is a sparse geometric estimation problem in which the parameters are a combination of feature coordinates, camera poses and calibration coefficients. It operates as a reconstruction refinement that provides an optimal (cost function minimisation) 3D structure and viewing (camera pose and calibration) parameters estimation [7]-[10],
- (iv) Dense multi-view 3D reconstruction that determines the correspondence for each pixel in spatially neighbouring images and produces a dense point cloud [11].

As with all 3D digitisation methods SFM-MVS has its limitations. It belongs to the *targetless* photogrammetric methods and relies on detecting points on a surface in order to calculate the intrinsic and extrinsic parameters of the camera, to determine the position and orientation of images in space and to perform the dense stereo. Hence, the existence of features on the surface of an object is associated with the ability of the method to reconstruct the scene and with the quality of the produced 3D data. Surfaces that exploit strong morphological features coupled with high frequency colour changes and low reflectance are considered as SFM-MVS friendly. Oppositely, applying SFM-MVS on reflective surfaces is a challenging procedure that involves the use of lens filters to minimise light reflections and abstract scattering effects.

Again, using SFM-MVS on featureless surfaces may result in erroneous image alignment or extremely noisy data. The quality of the 3D data produced by modern SFM/MVS software solutions depict the applicability of such methods in low budget digitisation or documentation projects. The semi-automated functionality of the software composes an efficient solution that also expects a low knowledge overhead from the user. It is for certain that each technology has its advantages and disadvantages. Thus, the different 3D acquisition technologies should always be considered as supplemental. Both 3D range scanners and image-based solutions can find their applications in the cultural heritage domain. 3D range scanners have already proven their great potential on acquiring high quality 3D data from complex structures in a fast and efficient way. Nevertheless, the incorporation of 3D range scanning along with topography and photogrammetry always lead to more accurate surveys.

Furthermore, SFM-MVS is offered as commercial and open source software solutions. The EU funded project 3D-COFORM has implemented an SFM-DMVR system as a Web-service [19]. Comparable systems have been created by Autodesk [20], Viztu Technologies [21] and Insight3D [22]. Eos Systems Inc. offers PhotoModeler Scanner [23]. The software is able to

reconstruct the content of an image collection as a 3D dense point cloud with the help of photogrammetric targets. Towards the same direction, Agisoft offers PhotoScan [24]. This software solution can merge the independent depth maps of all images and produce a single vertex painted point cloud that can be converted to a triangulated 3D mesh of different densities. Moreover, Pix4D developed the Pix4UAV software that is able to create 3D digital elevation models from image collections captured by UAVs [25].

Find below a list of SFM/MVS software implementations [18][26].

Open Source

C++

[Bundler - Structure from Motion for Unordered Photo Collections](#) by Noah Snavely
[openMVG](#) An Open Multiple View Geometry library + Structure from Motion demonstrators
[Libmv - A Structure from Motion library](#)
[Theia](#): A Fast and scalable structure-from-motion library released under the BSD license
[MicMac, a SFM open-source code released](#) by the [Institut national de l'information géographique et forestière](#)
[LSD-SLAM](#): Large-Scale Direct Monocular SLAM in real-time, by Jakob Engel
[MVE - The Multi-View Environment](#) by Simon Fuhrmann, TU Darmstadt
[SBA](#) for generic bundle adjustment by Manolis Lourakis

Matlab

[Structure from Motion toolbox for Matlab](#) by Vincent Rabaud
[Matlab Functions for Multiple View Geometry](#) by Andrew Zissermann
[Structure and Motion Toolkit](#) by Phil Torr
[Matlab Code for Non-Rigid Structure from Motion](#) by Lorenzo Torresani

Python

[Python Photogrammetry Toolbox GUI](#) - an open-source SFM GUI (Easy SfM and dense point cloud estimation launcher) by Pierre Moulon and Arc-Team

Other Sources

[Smart3DCapture](#), a complete photogrammetry solution by Acute3D.
[3DF Samantha - Command line structure from Motion pipeline for Windows](#), by 3Dflow srl.
[Automatic Camera Tracking System \(ACTS\) A structure-from-motion system for Microsoft Windows](#), by State Key Lab of CAD&CG, Zhejiang University.
[VisualSFM: A Visual Structure from Motion System](#), by Changchang Wu
[SFMToolkit a complete photogrammetry solution based on open-source software](#)
[MountainsMap SEM](#) software for [Scanning Electron Microscopes](#). 3D is obtained by tilting the specimen + photogrammetry.
[Voodoo Camera Tracker](#), non-commercial tool for the integration of virtual and real scenes.
Original site, archived: [Laboratorium für Informationstechnologie, University of Hannover](#)

[MetalO Toolbox](#) SfM for augmented reality on mobile devices.

[TacitView](#) by [2d3 Sensing](#)

[Catena](#) Python Abstract Workflow Framework with SfM components.

[123D Catch](#) by [Autodesk](#)

[3DF Zephyr](#) by [3DFLOW](#)

[3Dsom](#) by [Big Object Base](#)

[4E Software](#) by [4e Software](#)

[ARC3D](#) by [KU Leuven](#)

[Australis](#) by [Photometrix](#)

[Correlator3D](#) by [SimActive Inc.](#)

[DroneMapper](#) by [DroneMapper](#)

[ELCOVISION 10](#) by [PMS AG](#), [Leica Geosystems](#)

[EnsoMOSAIC](#) by [MosaicMill](#)

[Enwaj](#) by [Banzai Pipeline Ltd](#)

[ImageModeler](#) by [Autodesk](#)

[iWitness](#) by [Photometrix](#)

[Linearis3D Photogrammetry](#) by [Linearis3D](#)

[Match Photo](#) by [Trimble Navigation](#)

[Memento](#) by [Autodesk](#)

[PHOTOMOD](#) by [Racurs](#)

[PhotoModeler](#) by [Eos Systems](#)

[PhotoScan](#) by [Agisoft](#)

[PhotoSculpt](#) by [Hippolyte Mounier](#)

[PhotoSketch](#) by [Brainstorm Technology LLC](#)

[Pix4Dmapper Discovery](#) by [Pix4D SA](#)

[Pix4Dmapper Pro](#) by [Pix4D SA](#)

[RealityCapture](#) by [Capturing Reality](#)

[ReCap](#) by [Autodesk](#)

[RhinoPhoto](#) by [Qualup SAS](#)

[SMART3DCAPTURE](#) by [ACUTE3D](#)

[Metrology Engine](#) by [VisualSize](#)

[VI3DIM](#) by [Vi3Dim](#)

[VideoTrace](#) by [Australian Center for Visual Technology \(AVCT\)](#), [PunchCard](#)

[WebDLT](#) by [B. Molnar](#), [BME FMT](#)

2. Applying SFM/MVS for digitising movable and unmovable objects

In this paragraph we provide a set of primary - basic rules for applying SFM/MVS [12][13][16][17]. As with any new skill it is important to start with a simple and small project. Then, only when a small project has been handled successfully it is sensible to start working on larger and more ambitious ones. This is also true for SFM/MVS as it involves the use of a software tool and hardware that you need to get familiar with. A project with a low number of images is a good start. Additionally, make sure you read the bullet points below that are highly related to the data collection phase in order to get the best possible results even when applying the SFM/MVS method for the first time.

- Use a digital camera with reasonably high resolution (**>8 MPix**). Our experience in relation with the current computer systems specifications (in terms of memory and graphics card capabilities) indicate the use of a more than *10MPix* sensor (for large unmovable objects) camera DSLR or compact DSLR (mirrorless) is proposed. Note that it is important for that the acquired images not suffer from strong compression artefacts as they affect the quality of the produced 3D data [12].

For this summer school we will be using 20MPs mirrorless DSLRs. DSLR cameras tend to offer higher quality results than compact digital cameras. The number of megapixels is important as high resolution provides more information, but if the lenses are of low quality, images will lack of sharpness and clarity whatever the resolution. In addition, DSLR cameras normally provide more controls for image capture, so tend to be more versatile and hence capable of tackling more diverse problems.

Again, DSLRs offer the best high ISO performance - this allows working indoors without the need for a tripod or flash or to stop down aperture for increased depth of field [17].

- Wide angle lenses suit better for reconstructing spatial relations between objects than telephoto lenses.
- Distortions associated with fixed focal length lenses are easier to model and maintain than the more common, variable zoom lens.
- Variable zoom lenses (e.g. 18-70mm) cameras are more versatile and may be used for close range digital photogrammetry.
- Avoid not textured and flat objects or scenes (Featureless surfaces are SFM/MVS non-friendly). The object should have a photographic chromatic texture, with particular elements.

- Avoid both shiny and transparent objects. The object you try to digitise should not have an excessive natural or artificial light reflection.
- Avoid capturing unneeded foregrounds as well as moving objects.
- Shoot shiny items under a cloudy sky or within a light box where applicable.
- Take pictures using a large overlap (at least 60% overlapping between two images). According to [16], to maintain a consistent 66% overlap, the camera must be moved a distance equivalent to 34% of the camera's field of view between photographs, from left to right.
- In your photos the object must fill at minimum $3/5$ of the image plane.
- To assure a good 3D reconstruction, the object must be located at the centre of the photos.
- To achieve a good geometric resolution of the object, you have not to take pictures with excessive angle of camera. Avoid excessive angles of shooting (perspective).
- Ensure the entire subject is covered by at least three images. Three viewpoints is the minimum required for a successful 3D reconstruction.
- Avoid using flash light (in-built camera flash) and avoid too bright photos. If you want more brightness in your photos, you can have to take pictures at daylight setting up exposure values, ISO values, and colour in the camera's settings.
- Images should not have low brightness either. In order to prevent that you need to set up the exposure values, ISO values (at least 400) and colour settings of the camera.
- Use the lowest possible ISO setting. The higher the ISO setting, the more electronic noise is generated in the camera's sensor. This noise affects dramatically the pixel matching procedure performed between the different images.
- Turn off image stabilisation and auto-rotate camera functions. Such features should be disabled when collecting data for SFM/MVS projects as each captured pixel position must represent a repeatable measurement point.
- Use of UV filter and circular polarisation filter to reduce reflectance.
- Avoid taking pictures against a light (solar or artificial) as it will result strong shadows and high contrast.

- In order to acquire no blurry photos it is wiser to use a tripod and a remote trigger. Note that small amounts of image blur will reduce the apparent resolution of an image but larger amounts will reduce the image matching routines used by the SFM/MVS software.
- In some cases taping the focus ring in place has been mentioned in bibliography.
- Use prime lenses rather than zoom lenses. If a zoom lens must be used, try to use the nearest or farthest extent of the zoom in order to make sure it is kept fixed.
- The camera's aperture setting is proposed to remain constant during a capture of an images sequence. On a $35mm$ lens camera, it is good practice not to set the aperture smaller than $f/11$. With apertures smaller than $f/11$, diffraction effects occur that blur the image, significantly reducing the camera's resolution. As a rule of thumb in order to obtain the highest order results, ensure that the camera configuration does not change for a given images sequence.
- When shooting small objects set up your camera's aperture so that you get the deepest (largest) possible depth of field.
- Find and use the fastest shutter speed applicable to the current light conditions.
- Check all images in order to identify the *out of focus* and *blurry* images and remove them.
- Capture most important scene content and details from multiple viewpoints.
- Do not crop or geometrically transform the images for any reason. The resolution of the image in combination with the lens information stored in the EXIF header of the image file are parsed by the SFM/MVS tool in order to perform the 3D spatial alignment procedure. Processing the photos which were manually cropped or geometrically warped is likely to fail or produce highly inaccurate results. To estimate the field of view for each photo SFM/MVS tools use the information saved in the EXIF part of each image. If EXIF data are available you can expect to get the best possible 3D reconstruction.

However 3D scene can also be reconstructed in the absence of EXIF data. In the case of Agisoft PhotoScan for example the software assumes that the $35mm$ focal length equivalent equals to $50mm$ and tries to align the photos in accordance with this assumption. If the correct focal length value differs significantly from $50mm$, the alignment can give incorrect results or even fail [12]. Nevertheless, photometric modifications do not affect the 3D reconstruction results.

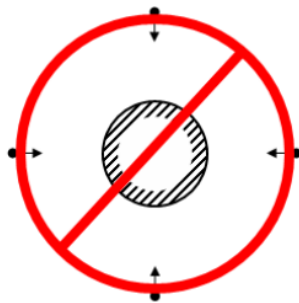
- In cases where EXIF information is not available, manual camera calibration has to be performed in order for the SFM/MVS software tool to model the lens distortion properties.
- Fisheye lenses and ultra wide angle lenses are often poorly modelled and it would wise to be avoided given the current state of the software tools available. This is because radial lens distortion becomes excessive for such lenses and thus reducing the potential accuracy.
- Data collection phase involves exposed conditions, heavy use and creating image sets on different days. This emphasises the important of using a stable data collection system e.g. camera.
- Keep in mind that taking more photos is always better than realising when back at office that you didn't get enough and thus cannot create a complete 3D model. Take additional images to improve data redundancy.
- Computer controlled turntables and sliders can semi-automate the data collection phase when capturing movable – isolated objects and thus dramatically reduce the data collection time duration. Such a system will be presented and used by the participants of this summer school.
- As the data input (image sets) defines the quality of the produced 3D reconstruction, try to develop your photographic skills so that you can provide the required camera settings that will result clear and sharp images under different light conditions.
- When *elevated* photos are required attempt to identify the optimum in terms of cost requirements and applicability between methods such as tall tripods, monopods, cranes, elevating platforms as well as UAVs and helicopters.
- Design your data collection approach. Prepare a plan for both terrestrial and aerial photo shooting sessions. Where probable, try visiting the site or review the object and take various test images to study prior to planning. Take under consideration the working conditions and other issues such as weather (sun & shadows), object's visibility and accessibility, equipment to be carried in situ, assistance requirements (digitisation team members), safety regulations, legal responsibilities and written permissions required when digitising parts of our cultural heritage thesaurus.
- When there is a need to define/set a reference coordinate system for the reconstructed 3D model, make sure to identify or place ground markers (photogrammetric targets) that will be used to set reference coordinate system and scale. Perform accurate reference distance measurements.

- **Terrestrial Data Collection approaches:** It is important to **start thinking in 3D** before initiating any data collection phase. Thus, you have to understand the 3D morphological features and structure of the object you are observing and the reasons you will be applying one of the data collections approaches described below and why you have to shoot turning around the object at 360° or 180° [13].

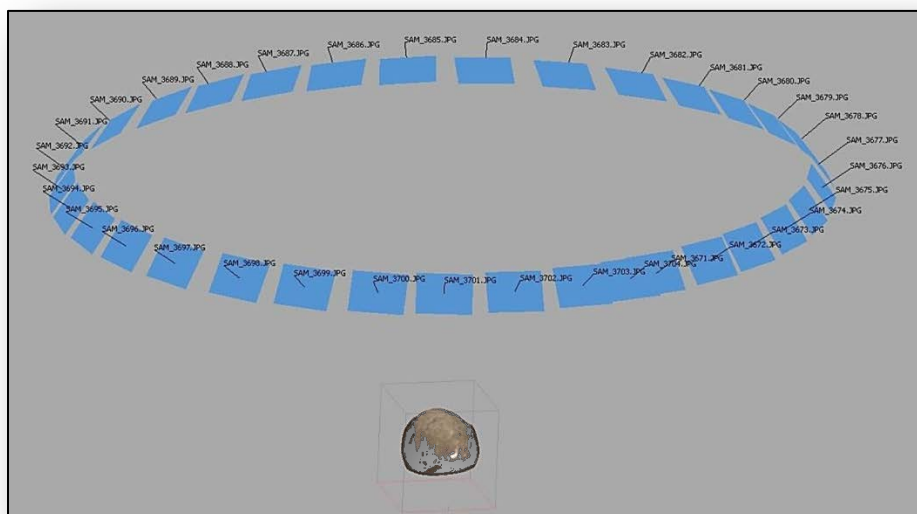
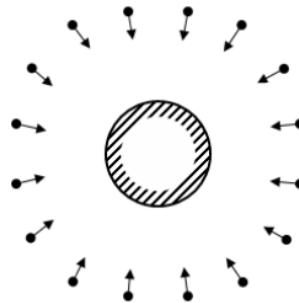
Because of the flexibility of the technique, it is possible to obtain high accuracy 3D data from subjects that are at almost any orientation (horizontal, vertical, above, or below) in relation to the camera's spatial position [16]. Below you will find a number of figures illustrating the data collection approaches that should be followed in order to digitise different types of objects.

- Photo shooting a movable object [12] (Create multiple closed-loops image sets from different angles). For round subjects, capture photos every 10 to 15 degrees and overlap the beginning and end photos to complete the loop:

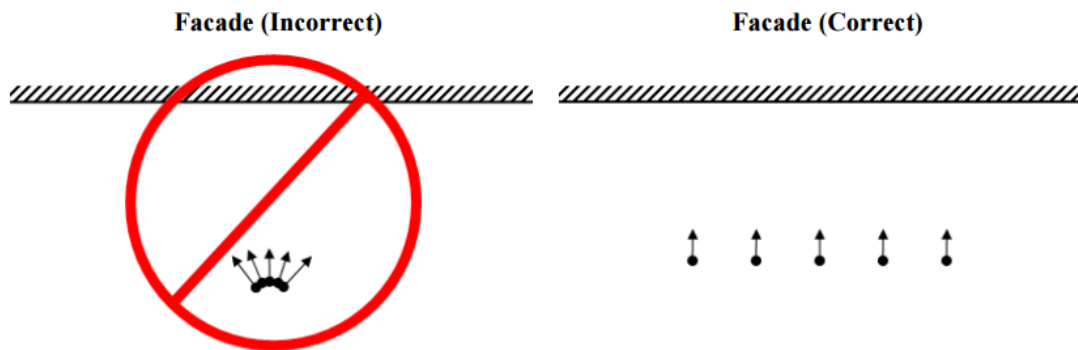
Isolated Object (Incorrect)



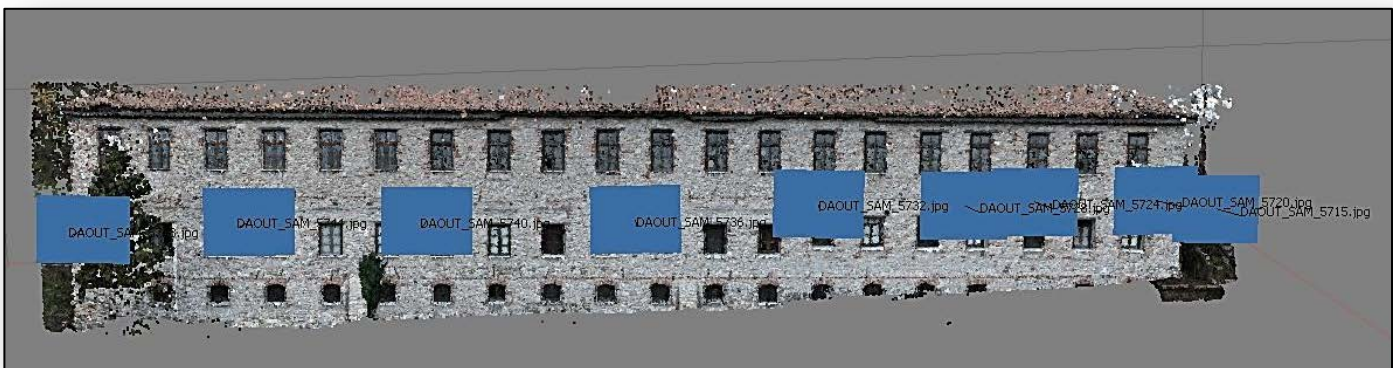
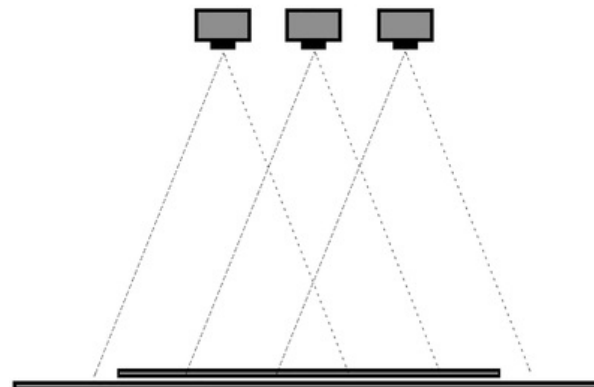
Isolated Object (Correct)



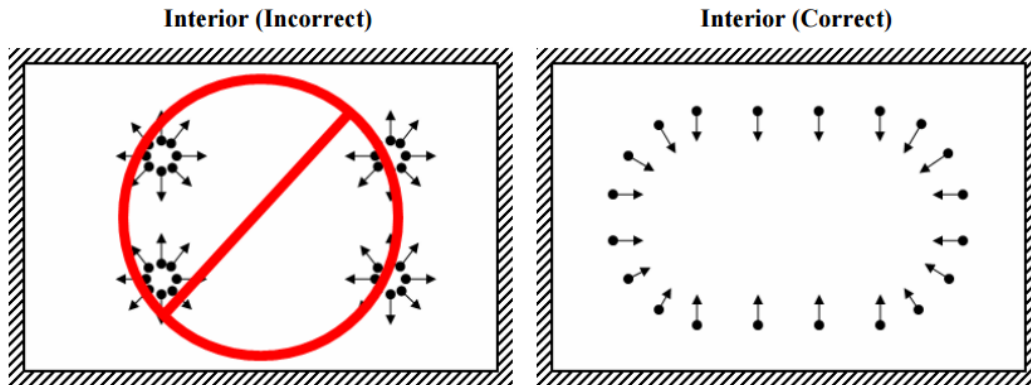
- ii. Photoshooting a façade – Parallel convergent shot [12][13]: Parallel shot works using a tripod with a slider where your camera can move at regular gaps, shooting always with at least 60% of images overlapping. Proceed systematically from left to right along the length of the subject and take as many photos as necessary to ensure complete coverage [16].



PARALLEL CONVERGENT SHOTS
UPPER VIEW

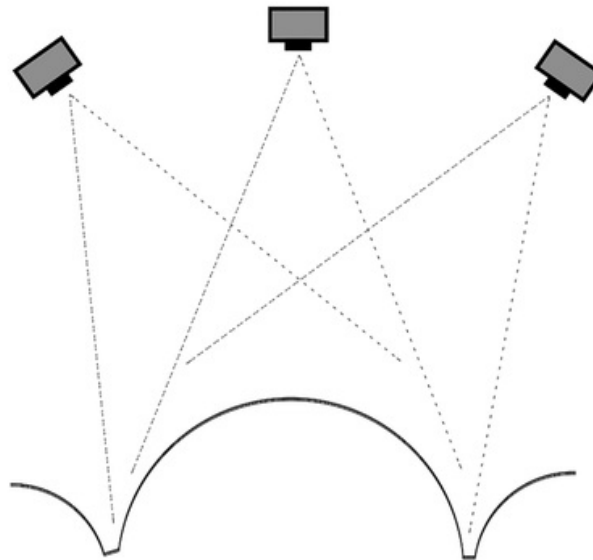


- iii. Photoshooting an interior [12]: This approach is used to reconstruct a room or the interior of a monument, etc. A number of image sets should be captured using different heights (*elevation*).



- iv. Photoshooting using convergent shot [13]: This data collection approach is used to reconstruct objects or buildings with low depth such as walls and masonry but it can be applied into other types of objects that reflect similar morphological features.

CONVERGENT SHOTS UPPER VIEW



3. Photoshooting distance and object dimensions

Here you may find some general guidelines on what distances should you use when trying to capture objects of different size. For small objects ranging from a few centimetres up to 30 centimetres height, a valid distance range (always relevant to the camera's lens and requirements of the digitisation project) is between *10cm* and *50 cm*. According to [13], a focal length between *3mm* and *12mm* along with the convergent shot technique is the way to go. In case of medium objects a distance range between *1m* to *3m* is recommended. For large scale projects and given the current processing power and memory restrictions of an average computer system the shooting range is found between *3m* to *6m*.

It would be appropriate at this point to mention the *Ground Sampling Distance* (GSD) which is the distance between pixel centres and the surface of the object (e.g. ground) [14]. GSD is originally defined as the flight height and as it was used in aerial photogrammetry. The bigger the value of the image GSD is, the lower the spatial resolution of the image is and thus fewer details are visible. For example a GSD of *5cm* indicates that one pixel of the image represents *5cm* on the ground (on the real world).

It should be noted that the image set created during a data collection cannot have a constant GSD. Thus, an attempt should be made for trying to maintain a consistent distance from the subject. A useful rule of thumb is that GSD should be at least 2-3 times smaller than the smallest detail required to be captured. Nonetheless, during the processing of the reconstructed 3D model, one can define a uniform/average distance between vertices.

The GSD for digital cameras is calculated using the formula below:

$$\text{GSD} = h_g / c_k \times \text{CCD pixel size}$$

Where h_g = flying height above ground and
 c_k = focal length

The pixel size of the CCD sensor can be calculated using the size of the sensor's long side as well as the number of pixels on the long side the image produced. For example a camera with a sensor size of **23.5** x 15.7mm and an image resolution of **5472** x 3648 (ratio 3:2) has a pixel of $23.5/5472 = 0.0042945$ mm = 4.2945 μm . Generally and depending on the CCD manufacturer, there are CCDs with pixel size varying from 4 to 12 microns. For each digital camera, the combination of focal length and pixel size determines its operation profile.

Furthermore, another aspect that affects the data collection phase is the B/D ratio. The *image base – distance to object* ratio is the distance between the camera and object in relation to the distance between two consecutive capturing viewpoints. According to [15], a strong image Base – Distance to object (B/D) ratio ensures high depth accuracy in photogrammetry projects. However the resulting significant dissimilarity and occlusions will lead to limited matching's success for SFM/MVS methods. An acceptable B/D ratio to achieve high accuracy has been reported in various publications and ranges from 0.16 to 0.5 or even higher. Generally the depth error increases significantly when the B/D ratio decreases below 0.3.

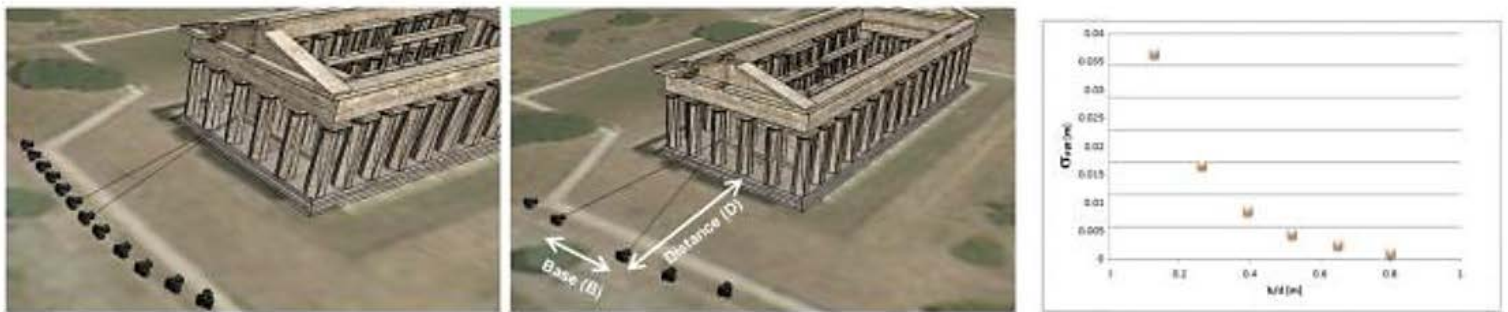


Figure 1 Image Base / Distance to object ratio visualisation

Furthermore, some important camera parameters that are related with photoshooting distance and the actual content of each image are the aperture, shutter speed and ISO. The following figure explains the impact of each parameter value on the image's content. Please note in the figure below the effect of a small aperture on the depth of field and the effect of a fast shutter speed.

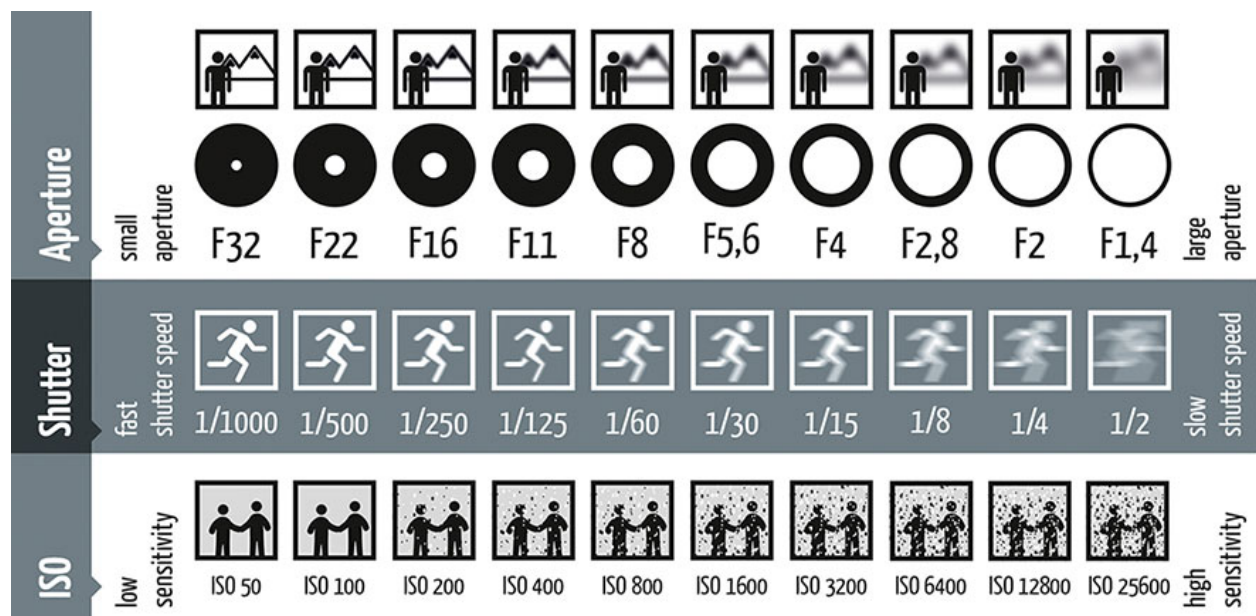


Figure 2 Camera's primary settings explained [27]

Briefly, aperture is the size of the opening in the lens through which the light travels while shutter speed (also known as exposure time) determines the amount of time that the shutter of the camera remains open. All the time that the shutter is open light reaches the sensor of the camera.

Furthermore, as SFM/MVS reconstructs the scene from an image set proportionally correct but in an abstract reference coordinate system there is a need to use photogrammetric targets and scale bars in order for the 3D model to reflect real world dimensions and give the user the ability to perform distance measurements between any points on its surface. There are numerous products available that can support your indoor or outdoor projects. Some important aspects are their accurate and individual calibration, optimised for long-term outdoor use, water and environment-resistant, different types of encoding that meet the various needs of a digitisation project and high frequency details to be able to reconstruct in 3D the scale bar itself. Some software tools such as Agisoft Photoscan Professional detects a specific type of targets (*12-bit coded targets*) found in the image set and automatically find the exact centre of the targets. Then by knowing the size of the scale bar that carries the targets is given to the tool and it automatically performs the model's scaling and thus measuring any feature becomes possible.



Figure 3 Example of a code bar with targets and rich gray scale background for efficient 3D reconstruction [16].

In large scale projects, targets are used to define the ground control points (GCPs) and their position coordinates are known or measured using a real time kinematic receiver (GNSS – Global Navigation Satellite System). When such coordinates are used; the model is geo-referenced and apart from distance measurements, location identification of features in real world coordinates (longitude, latitude) is also possible.

4. Materials that can be & cannot be reconstructed by using SFM/MVS [13]

FRIENDLY MATERIALS

NATURAL STONE	SOIL
ARTIFICIAL STONE (manipulated)	MARBLE (not white)
BONES	WOOD
LEATHER	SANDSTONES
IRON	BRONZE
COPPER	GOLD
PLASTER	POTTERY
BRICKS	

NON- FRIENDLY MATERIALS

WATER	GLASS
PLANTS AND VEGETATION	VARNISH
MONOCHROMATIC GLOSSY SURFACES (Featureless Surfaces)	WOOD
STEEL	PLASTIC (Featureless)
GLOSSY GOLD	GLOSSY IRON
GLOSSY COPPER	GLOSSY BRONZE

5. Examples of unusable images

Find below a number of image examples that are considered unusable for SFM/MVS projects due a number of typical mistakes.



- Flash light – Different and Harsh shadows
- Bad background – Reflections
- Featureless surface
- Too bright



- High contrast
- Reflective effects
- Strong shadows
- Vary dark colours



- Excessive camera angle (perspective)
- Photo against solar light – Glaring effects



photos against the solar light
reflective and glaring effects
object not at the centre of the
photos [13]



Object appears too far
Monument is too big to be
reconstructed with a small
number of images. Can be
done but the quality of the 3D
data would be very low.



Reflection effects
Reflective surface
Featureless surface



Low brightness
Flash light – Different and
Harsh shadows
Strong shadows



Low brightness
High ISO value
Bad depth of field – focus [13]



Low brightness
Object appears too far

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