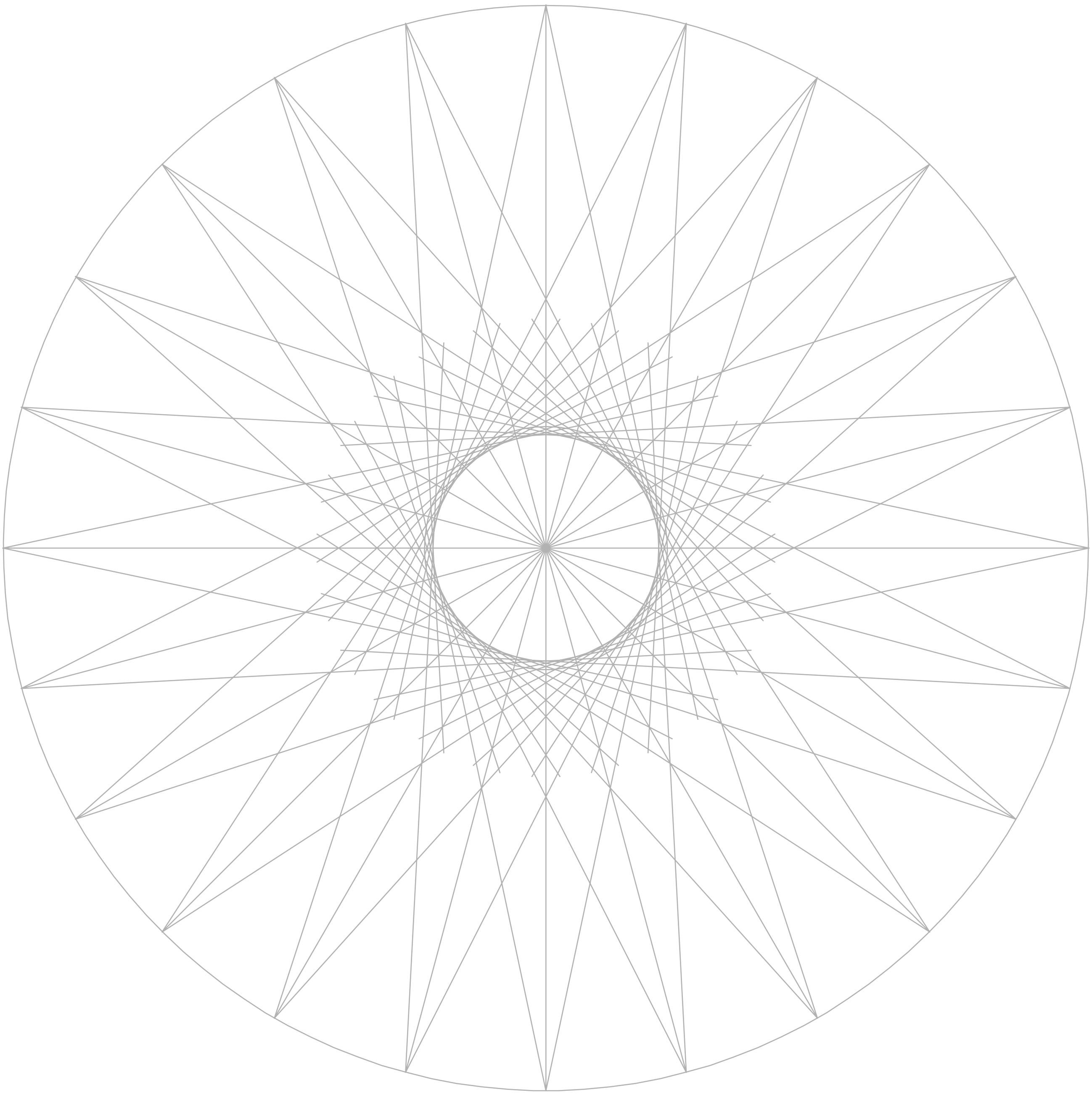
ON THE POPULARIZATION OF DIGITAL CLOSE-RANGE PHOTOGRAMMETRY:

A HANDBOOK FOR NEW USERS.



ON THE POPULARIZATION OF DIGITAL CLOSE-RANGE PHOTOGRAMMETRY:

A HANDBOOK FOR NEW USERS.

for the

Post-Graduate GeoInformatics
School of Surveying-Engineering,
National University of Athens,

Thesis by attendant
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under the
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FOREWARD

Why this choice of subject?

This handbook describes the current "snapshot" of the evolution process of **Photogrammetry,** a centuries-old[1] and up to now expert-exclusive discipline. Photogrammetry has traditionally been a "tool of the trade" in the arsenal of the surveyor-engineer, serving the need for accurate spatial/geometrical documentation. Photogrammetry in the past was a complicated and labour intensive process, which was available only to a small circle of experts and which had a specific scope of applications, with a heavy focus on cartography. The aforementioned «expansion» has been triggered by the advent of **Digitization**, in specific, by the digital sensors and the automation of the calculations & techniques involved in the photogrammetric process. The constant development of computer algorithms, alongside the improvement of the necessary hardware, has greatly amplified the **efficiency** and **affordability** of digital photogrammetry. Nowadays, it can potentially offer its benefits to a much wider audience, including experts from different disciplines or even non-expert users. For this process of "**dissemination**", the soft- & hardware availability does not present itself so much as a problem, as "public awareness" & practical, technological knowhow do. At this evolutionary point, there is a great need for widespread **information** on the potential of digital photogrammetry and more importantly, for theoretical & practical **training** of the new user groups.

> This effort is a (very) small step in this direction.

What is the scope of this effort:

This work has a double «aim»: it aspires to be **informative** for those of technical expertise (professionals, academics, etc.) but also **educative** and practically useful for unspecialized personell, who might have a personal interest in the mentioned techniques and their abilities. Trying to serve this two-sided goal has dictated the contents and the structuring of this paper.

Since photogrammetry is a relatively new and yet uncommon field of knowledge to the public, it is deemed useful to conduct a formal -but brief- introduction to the discipline (*Section A*).

In order to appreciate -& successfuly use- photogrammetry, it is important to discover the layers of knowledge underneath. Therefore, a theoretical background on a wide variety of topics is provided, so as to better facilitate the reader's familiarization with the subject (*Section B*).

Finally, the goal is the presentation of the currently available photogrammetric workflows for the acquisition of 3d object geometry in a way that can initiate experimentation on behalf of the potential reader (*Section C*).

1 We could roughly pinpoint the appearance of applied photogrammetry around 1850.

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SECTION A)
CRASH COURSE

<abstract>

The flow of this introduction is determined by answering 4 questions:

-What is Photogrammetry?

-Why is it "relevant" today?*

-What are the contemporary applications of Photogrammetry?

-What does a person needs to know to adequately understand Photogrammetry, at least in principle, in the 21st century?

** The term «relevant» is usually used with relation to something. In this case, it is elliptically stated to express the innovative potential of the method on a variety of situations that occur in our contemporary conditions.*

CONTENTS

WHAT IS PHOTOGRAMMETRY?

Before rushing off into a single, unifying definition of Photogrammetry, an attempt will be made to approach the term through a multiplicity of ways:

> By Etymology:*

The word «Photogrammetry» (/ˌfəʊtə(ʊ)ˈgramɪtri/) is a composite word stemming from the conjunction of the Greek words for «φως» -meaning “**light**”-, «γραμμή» -meaning that a **drawn line**- and «μέτρο» -meaning “to **measure**”. It therefore signifies measuring graphically by means of light[1].

«φως» + «γραμμή» + «μέτρο»

** On the origin of the term*

As early as 1851, a military engineer in France, Aimé Laussedat (for more see next chapter) had begun experiments to use images for topographic mapping purposes. In the early period he worked with hand drawn images, acquired with the help of an optical tool for perspective drawing, the “camera lucida”. He named his method “**Iconométrie**”. Later he started to apply photographs, and in 1859 the prototype of a topographic camera was built to his specifications. He called his system “**Métrophotographie**”. Other names applied to the method in subsequent years include “**Photométrographie**” and “**Photographométrie**”. Albrecht Meydenbauer, a German architect researching the exact same concept at that time (for more on all this, see next chapter), published an article in No. 14 in the “Wochenblatt des Architektenvereins zu Berlin[2]” on April 1867, under the title “**Die Photometrographie**”. Dr. Otto Kersten, a geographical explorer, after getting acquainted with this new-found practice and deeply interested by its potential proposed the simpler & shorter term “**Photogrammetrie**”. Indeed, Albrecht Meydenbauer substituted and introduced the new term “Photogrammetry” in No. 49 on December of 1867, which soon became the worldwide accepted title of the discipline.[3]


WOCHENBLATT
HERAUSGEGEBEN VON MITGLIEDERN
DES ARCHITEKTEN-VEREINS
ERSTER JAHRGANG
1867.

The term “Photogrammetry” becomes established by the publication of Albrecht Meydenbauer in the 1867 newsprint of the Berlin Architect’s Society[4]

> By Definitions (from various sources of unequal reliability):

Wikipedia:

Photogrammetry is the **science** of making measurements from photographs by recovering the exact positions of surface points.

Oxford Dictionary:

1 Whitmore, G.D. & Thompson, M.M. (1966), «Introduction to Photogrammetry», American Society of Photogrammetry, v.1, p.1-16.
2 Weekly Journal of the Association of Architects in Berlin
3 Joerg Albertz, “A look back, 140 Years of Photogrammetry: Some Remarks on the History of Photogrammetry”, web article
4 Image Source: https://upload.wikimedia.org/wikipedia/commons/thumb/0/0c/1867_Ueber_Touage_auf_der_Loire.pdf/page1-1239px-1867_Ueber_Touage_auf_der_Loire.pdf.jpg

The **use** of photography in surveying & mapping to ascertain measurements between objects.

Collins Dictionary:

The **process** of making measurements from photographs, used especially in the construction of maps from aerial photographs and also in military intelligence, medical and industrial research, etc.

Merriam-Webster Dictionary:

The **science** of making reliable measurements by the use of photographs and especially aerial photographs (as in surveying).

Close Range Photogrammetry - Luhmann, T. et al, 2006

Photogrammetry encompasses **methods** of image measurement and interpretation in order to derive the shape and location of an object from one or more photographs of that object.

Close Range Photogrammetry and Machine Vision – K.B. Atkinson, 2003

Photogrammetry is the **science, and art**, of determining the size and shape of objects as a consequence of analysing images recorded on film or electronic media.

> American Society for Photogrammetry and Remote Sensing (ASPRS):

Photogrammetry and Remote Sensing are the **art, science and technology** of obtaining reliable information about physical objects and the environment, through a process of recording, measuring and interpreting imagery and digital representations of energy patterns derived from non-contact sensor systems.[5]

Notes:

The above definitions vary in their approach and also, focus on different aspects of Photogrammetry. From the general resources (dictionaries) we note an identification of photogrammetry with its practical application (aerial/map-making). Other resources(wikipedia) focus more on the actual concept ("..recovering positions of surface points.."), rather than its scope and purpose. Photogrammetry is vaguely presented either as a science or a practical art or a technological feat or a combination of the above. All resources have the notion of the photograph and the measurement in common, but the ASPRS makes direct reference to the more general, parent-category (any record derived from sensors, that can be imaged). The ASPRS also broadens the type of information that is yielded (not only geometrical).

Summary:

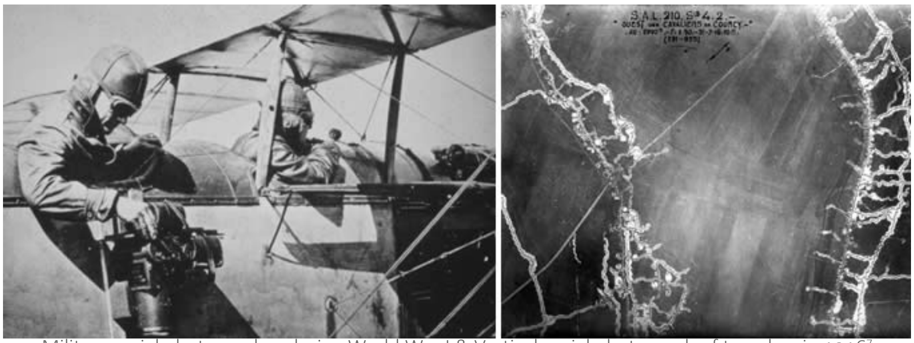
Summing up, rather than be confined to a specific kind of images or a specific range of applications, we can present photogrammetry as a "**measuring tool for everything that can be imaged**."[6]

5 McGlone, (2004), Manual of Photogrammetry (5th Edition), ASPRS. The substitution of the word "photography" with "pattern of electromagnetic radiant energy and other phenomena" reflects the recognition that imagery may be acquired, not only through the use of a conventional camera, but also by recording the scene by one or more special sensors, including multi-spectral scanning (Thompson and Gruner, 1980).

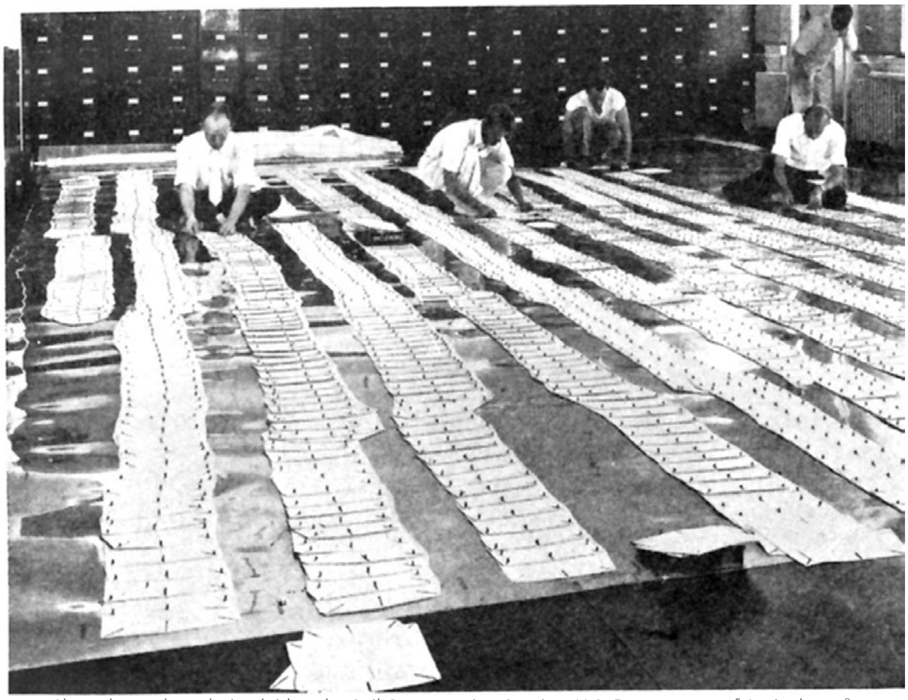
6 Prof. Andreas Georgopoulos, 2015, CULTURAL HERITAGE PHOTOGRAMMETRY, Innova, Virtual Archaeology International Network

> By its Practical Implementation (Historical Significance)

Historically, photogrammetry has been one of the “**tools of the trade**” of the surveyor engineer, alongside Topography, Geodesy, Cartography etc. The development of photogrammetry can be traced back to the middle of the 19th century by a series of entrepreneurs. Its foundation lies on a combination of experimentations and advances in photographic devices, optical lenses and analytical formulations of geometrical problems. Its evolution is closely connected with that of photography and aviation and its application scope during the early period was in map-making and military applications.



Military aerial photographer during World War I & Vertical aerial photograph of trenches in 1916[7]



Slotted templates being laid at the Soil Conservation Service, U.S. Department of Agriculture.[8]

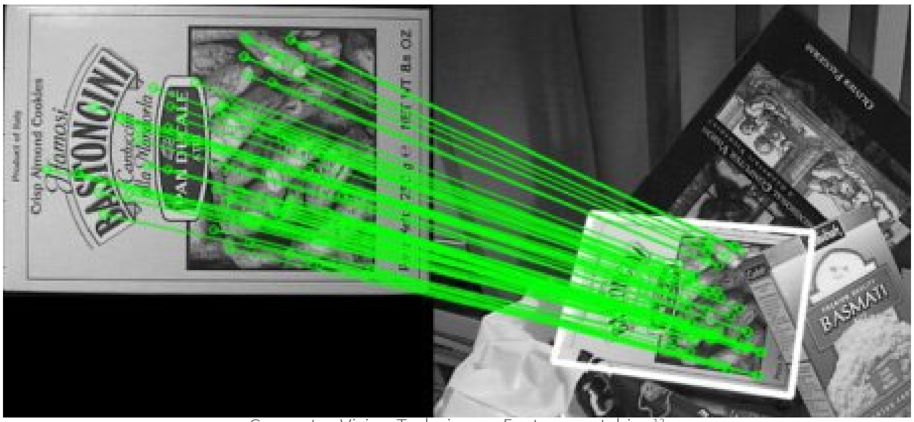
7 http://professionalaerialphotographers.com/content.aspx?page_id=22&club_id=808138&module_id=158950

8 Collier, Peter. “The impact on topographic mapping of developments in land and air survey: 1900-1939.” Cartography and Geographic Information Science 29.3 (2002): 155-174.

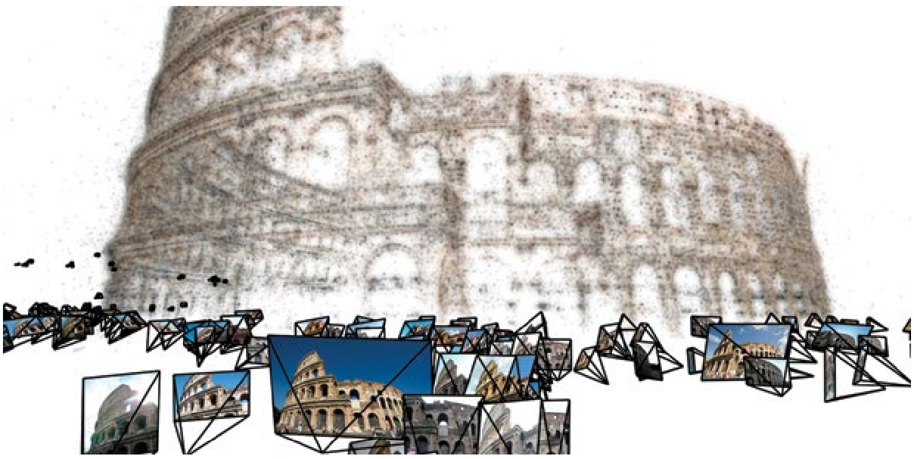
> By its Academic Stature (Scientific Course)

Photogrammetry, in terms of academic faculties, is an **engineering discipline** and traditionally falls under the broader discipline of **Surveying**. It is regarded as a “sister” discipline to **Remote Sensing**[9], with which it shares many common elements[10], since both used to rely up to recent years on the same source material (namely, aerial and satellite photography). Their familiarity is also true in essence, since Photogrammetry is a technique that requires **no physical contact** with the object under observation in order to yield useful data about it, as explicit in the name “Remote Sensing”. As to their differences, Remote Sensing emphasizes qualitative over quantitative information (analysis and interpretation of photographic images) and finds application in a wide variety of scientific disciplines, while Photogrammetry is a metrical science at heart (production of maps and precise 3d position of points), which has expanded its application range in the last 25 years.

Since the 1970’s photogrammetry has been more closely connected with the realm of **Computer Science** and in specific with the field of **Computer Vision**, since both revolve under the same issues/problems from a different perspective. From 1990 and onwards, we can note a significant merging of these 2 scientific fields, with developments mutually influencing each other. Nowadays, digital close-range photogrammetry has direct links to photographic science, computer graphics and computer vision, digital image processing, computer aided design (CAD), geographic information systems (GIS)[11].



Computer Vision Techniques: Feature matching[12]



Building Rome in a Day Project- Reconstruction of Colosseum from web-sourced photographs[13]

9 “Remote sensing may be broadly defined as the collection of information about an object without being in physical contact with the object. Aircraft and satellites are the common platforms from which remote sensing observations are made. The term remote sensing is restricted to methods that employ electromagnetic energy as the means of detecting and measuring target characteristics” (Sabins, 1978).

“Remote sensing is the art and science of obtaining information from a distance, i.e. obtaining information about objects or phenomena without being in physical contact with them. The science of remote sensing provides the instruments and theory to understand how objects and phenomena can be detected. The art of remote sensing is in the development and use analysis techniques to generate useful information”(Aronoff, 1995).

10 This is also manifest in national & international organizations, such as International Society of Photogrammetry and Remote Sensing (ISPRS).

11 Luhmann, T. et al, “Close Range Photogrammetry”, 2006, Whittles Publishing

12 http://opencv-python-tutroals.readthedocs.org/en/latest/_images/homography_findobj.jpg

13 https://grail.cs.washington.edu/rome/

SHORT OVERVIEW OF THE PHOTOGRAMMETRIC METHOD

Photogrammetry claims to be able to reveal 3d geometrical information about an object from its images. To be more accurate, photogrammetry can yield accurate measurements about an object **by constructing & measuring a reliable model of it**[14].

How is this achieved?

Photogrammetry at its core is based on the accurate understanding of the photographic process- namely, of the way that light rays (electromagnetic radiation) form images of objects on appropriate surfaces with the help of specifically-designed “devices”, such as the human eye or the photographic camera. These two devices share a common format: they are both equipped with a method to regulate the path of the light-rays by means of an adjustable opening (aperture) and they are equipped with a lens (or lenses), so that the light rays are guided and focused on a the surface of a sensor in a “meaningful” way, finally forming a picture. The rules governing this process are given by the field of **Geometric Optics** (for the way that light travels rectilinearly in space and interacts with material objects by means of reflection, refraction, etc.) and by the geometrical model of **Central Projection** (for the way that light forms a picture on the sensor device). An important factor for the advancement of photogrammetry was the analytical formulation of the projective transformation (as opposed to graphical).

It follows, then, that in photogrammetry the **photographic camera** is a tool: a measuring instrument that records directions of light paths in space[15], whose operation can be described (under conditions) by the mathematical model of central projection.

Since geometrical models (like the model of Central Projection) are based on abstractions of reality, photogrammetry needs to make up for the “physicality” of the instruments, which impart a degree of distortion on the final photograph and subsequently on all the following calculations. Therefore, as a preliminary step, photogrammetry needs to know aspects about the internal setting/construction of the photographic camera and information about the way that the imperfections of the lenses impart distortions on the photographs. This in photogrammetric terms is called **interior orientation**. The process of estimating the interior orientation parameters of a specific camera is called **calibration**. These parameters can be input as coefficients in the mathematical equation that describes the central projection model (**analytical approach**), thereby making up for the uniqueness of the camera and re-establishing the accuracy of the model.

As anyone can tell from experience, the next important piece of information is the relative location of the sensor device to the target object. Depending on the position of the viewer/camera, different areas of the target object are within the field of view- from each one of the “points” of the object, a light ray originates that will form a corresponding image of that point on the sensor surface. Only depicted parts can be processed and calculated later on (this includes parts out of field of view, occluded/hidden parts, but also anything that cannot be registered because of lack of contrast (areas in extremely bright light or in shadow), as well as details that cannot be recorded at a given viewing distance due to their relative size to the image scale). Therefore, the knowledge of the position of the sensor relative to the “outside world” is very important. This step is basically the alignment of the photographic surface/image plane in space -and therefore of the respective camera- and yields additional parameters to the aforementioned mathematical equation. For our convenience, instead of the combination “surface plane/projection point”, we can visualize the alignment of the bundle of light rays in space, which formed the photograph.

With only a single image of the subject and no additional information, the latent 3d information in the picture cannot be retrieved. Thanks to a basic photogrammetric concept, the **collinearity equation**, we have a clear understanding that the real point, the projection centre of the camera and the image point lie in a single straight line, the line of the light ray. But we cannot achieve the **3d restitution** -the calculation of the 3d coordinates- of the point, since we have no knowledge of where exactly the point lies on that straight line.

To achieve this, (at least) two images of the same point taken from different positions in space are needed. The “real” point in space lies at the intersection of its corresponding light rays. This process, known as **triangulation** or **intersection**, leads to the estimation of the 3d coordinates of the surface point of the subject. This takes place for every imaged point that we can identify between two images. The 3d geometry of

14 Georgopoulos, A., 1978. The science of Photogrammetry. A simplified approach and explanation of the three-dimensional spatial model concept. Technika Chronika, Vol. 8/78, pp. 8-12. August 1978

15 Thompson, E. H., 1957. The geometrical theory of the camera and its application in photogrammetry. The Photogrammetric Record (1957), 2 (10:240-263.

the subject starts to take shape.

The fundamental photogrammetric problem is therefore to describe the relation between a set of images and the target. Given this, a thorough understanding can be attained on how a 3dimensional object will be depicted on the 2dimensional surface[16] and vice-versa. For this purpose, the positioning of the bundles in 3d space is performed by various methods. One method is the exact positioning of the cameras, which is called **exterior orientation**. Another approach is to establish the relationship between cameras first, termed **relative orientation** and to position this configuration in space, afterwards, termed **absolute orientation**. Another method is the iterative approach to the positioning of cameras in space, termed **bundle adjustment**[17]. Bundle adjustment can establish the 3d location of points but will also yield a scaleless model. It is a process that can reveal the shape but not the size of the object. For this to be achieved, a single length measurement is adequate. This is done either by placing a scale bar near the photographed target, which will be included in the calculation of geometry or by measuring a length on the actual subject.

The **georeferencing** of the subject is its positioning in the world, stated in coordinates in some geodetic system (datum). The georeferencing process of the reconstructed model of course implies also the establishment of the correct scale (placing the subject in its original dimension in space).

16 Even if that picture is drawn by a human hand (as in perspective realistic paintings) or by the light rays themselves (as in photo-graphy")
17 Bundle adjustment also recomputes the shape of the bundles.

> Photogrammetric Products:

The primary purpose of a photogrammetric measurement is the three dimensional reconstruction of an object in **digital form** (coordinates and derived geometric elements) or **graphical form** (images, drawings, maps)[18]. The output product of digital photogrammetry can be **3d geometry** in various file formats, as they have been developed during the past years by the field of Computer Graphics. It can also involve images in raster formats containing **colour information** about each point of the surface, derived from the primary photographic input. The photogrammetric products, hence, can be divided in two categories:

3D / geometry

- 3D models of objects at various levels of detail and in various file formats, with or without colour information (textured models)

2D / images

- Orthophotos/Rectified Photos
- 2d Vector Drawings

** Short, helpful definitions of above terminology:*

- 3d Model

Any representation of 3d geometry created with specialised computer software. There are numerous ways for the geometrical information to be created (3d modelling techniques) and stored (file formats). The model may be used as a digital 3d object in an appropriate environment, incorporated in video animations or used to export still images of it.

- Textured Model

The term “texture” refers to a two-dimensional image file, also called a colour map, that is applied on a given 3dimensional surface/mesh for rendering/imaging purposes. The final, textured model combines geometrical and colour information.

- Orthophoto/Rectified Photo

A photographic image of an object is implied that is in an orthogonal projection, thus able to provide reliable metrical information about its geometry (given, of course, the scale with which the object was captured at the photographic image) along with qualitative information through the image texture. In this sense, the photographic image can be used as a fully textured “map”. The transformation process of an image from a perspective projection to an orthographic projection of a planar object is called rectification. It is the only case where a single image may yield metric information, as the object itself lacks the third dimension.

- 2d Vector Drawing:

The result of an image-based measurement work is typically exported in vector format which can then be further processed in a CAD or vector drawing program.

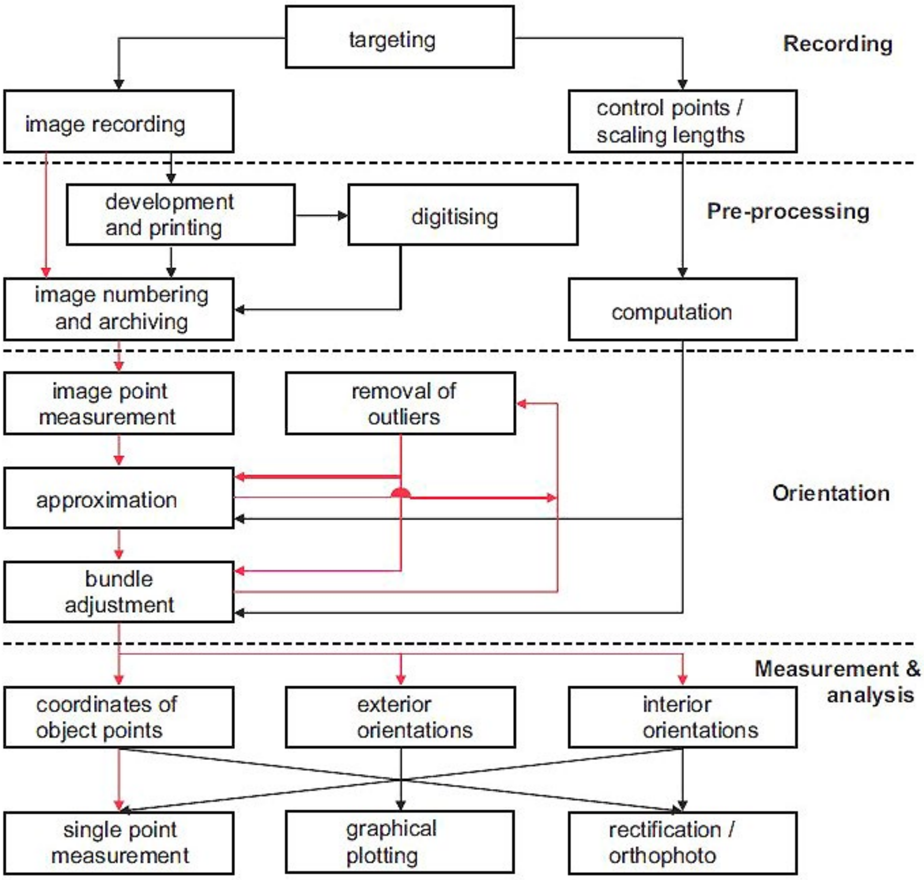
** Further elaboration on all of the above is provided at the appropriate positions later on in the manual.*

18 Luhmann, T. et al, “Close Range Photogrammetry”, 2006, Whittles Publishing

> Summary of Process / Graphic representation as a system[19]:

Input: Field Data	Computation	Output: Product
Geodetic Measurements Image Capture	Bundle Adjustment / Block Orientation	3d Geometric Models Image Files

Source Material		Photogrammetric Apparati	Product List
camera> sensor >	photographs | scanner | digital imagery	Rectifier Orthophoto Projector Comparator Stereoplotter Analytical plotter Softcopy Workstation	Image Products: - Rectifications - orthophotos Point Clouds Textured Surface Meshes Maps / Drawings: - topographic maps - special maps



Record and analysis procedures (Red can be automated)[20]

19 Schenk, T. (2005) "Introduction to Photogrammetry", Department of Civil and Environmental Engineering and Geodetic Science, The Ohio State University.
20 Luhmann, T. et al, "Close Range Photogrammetry", 2006, Whittles Publishing

ON THE “KINDS” OF PHOTOGRAMMETRY

Close-range vs. Aerial photogrammetry

At this point we can make a distinction, for purely practical reasons, between two “types” of Photogrammetry that differ only on the respective camera location during photography. So, we have on the one hand “Aerial Photogrammetry”, which uses photographs from specialized metric cameras mounted on aerial vehicles of different sorts. On the other, we have “Close-Range Photogrammetry”, which in effect describes any project using cameras on the ground to photograph the target. Since that is obviously from a closer range than that of an airflight, the name “Close-Range Photogrammetry” is self-explanatory and even more, the name itself subtly denotes the importance that aerial photogrammetry had in the past years. Furthermore, this difference implies of course also a difference in the range of possible targets.

Aerial photogrammetry is more closely connected to traditional surveying and map-making needs, ideal for sites of interests, natural landscapes, large-scale natural phenomena, etc.

“In Aerial Photogrammetry the camera is mounted on an aircraft and is usually pointed vertically towards the ground. Multiple overlapping photos of the ground are taken as the aircraft flies along a flight path. These photos are processed and used for the creation of Digital Elevation Models (DEM).”[21]

* In the same spirit, we can note here the term “Space (or Satellite) Photogrammetry”, which uses images received from sensors mounted on satellite devices. These sensors are usually much more sophisticated than normal or metric photographic cameras and can record a great range of non-visible wavelengths.

Close-Range photogrammetry can be applied to a range of target objects, as large as architectural monuments to as small as fragments of cultural heritage relics and in effect, anything that can be successfully imaged with a different variety of sensors. Objects as small as ≈0.1m or as large as 100m can be recorded, given the correct equipment (camera/lens) and setting.

“In Close-range Photogrammetry the camera is close to the subject and is typically hand-held or on a tripod (but can be on a vehicle too). Usually this type of photogrammetry is non-topographic - that is, the output is not topographic products (like terrain models or topographic maps), but drawings, 3D models, measurements and point clouds. Everyday cameras are used to model and measure buildings, engineering structures, forensic and accident scenes, mines, earth-works, stock-piles, archaeological artifacts, film sets, etc. This type of photogrammetry (**CRP** for short) is also sometimes called **Image-Based Modeling**(**IBM**).”[22]

A more detailed categorization by camera position and subject size follows[23]:

Satellite photogrammetry	processing of satellite images, h > ca. 200km
Aerial photogrammetry	processing of aerial photographs, h > ca. 300m
Terrestrial photogrammetry	measurements from a fixed terrestrial location
Close range photogrammetry	imaging distance h < ca. 300m
Macro photogrammetry	image scale > 1 (microscope imaging)

Single Image, Stereo and Multi-View Photogrammetry

Another practical distinction is based on the amount of images used for the photogrammetric processing and the corresponding methods as well as capabilities of establishing the space coordinates of the image points.

Single Image Photogrammetry is a self-explanatory term, denoting the fact that measurements about the object are taken from a single photograph. For this to be achieved, additional information about the location of depicted points is required, which the user needs to measure by methods of his choice. For every flat surface depicted, a minimum of 4 well-distributed, geodetically measured points (also known as **Ground Control Points**, **GCP**) or a few lengths (in the vertical and the horizontal direction) are necessary for the fulfilment of the equation that will then allow the calculation of the co-ordinates of any other point

21 http://www.photogrammetry.com/
22 Ibid.
23 Luhmann, T. et al, “Close Range Photogrammetry”, 2006, Whittles Publishing

that lies on the same surface. The limitations of this method are obvious and many, but projects like historical building facades which lack relief can be tackled with speed and ease, as well as other mostly man-made, simple geometrical items.

Stereo Photogrammetry is the process of 3d point restitution by the stereometric viewing of a suitable pair of photographic images. The stereo viewing of the images is a necessary requirement to "trick" the brain into an illusion of depth perception, thanks to parallax (for more on this, see next section). The photo-shooting for this process needs to follow certain, important rules in order for the stereoscopic viewing to be successful. The process needs manual input of the image point identification between two images (tie points), the geodetically measured Ground Control Points, as well as the camera interior orientation parameters. Finally, after successful block orientation, the 3d point restitution process is made manually by the user.

Multiple-Image Photogrammetry is the automated, computer vision evolution of the photogrammetric process. The process entails taking pictures (either analogue film or digital camera images) from different overlapping view perspectives, but not rigid planning as in stereophotogrammetry. The feature detection and matching between all image pairs is automatically computed and manual input can be required for corrections and optimisations. The interior-exterior orientation process is solved at the same step, thus eliminating the need for beforehand knowledge of the camera parameters. The 3d point restitution is also automated by the generation of various densities of point clouds. Multi-image Photogrammetry is a significant new era for the photogrammetric method.

Summary table

Single image photogrammetry	single image processing, mono-plotting, rectification, orthophotographs
Stereophotogrammetry	dual image processing, stereoscopic measurement
Multi-image photogrammetry	n images where n>2, bundle triangulation

ON THE CHARACTERISTICS OF PHOTOGRAMMETRY

> On the multiple dimensions of derived information

It is true that photogrammetry is foremost preoccupied with geometry: photogrammetry succeeds in offering geometrical data about the shape and size of the object of interest. But we can further state that photogrammetry also has the added benefits of a photographic documentation, as a result of the fact that photographs are being used as source material. Photographs are an inexpensive and rich data acquisition method.

For example, in terms of binary data, the colouring and texture of the object under study are also documented and mapped on the resulting 3d model. Apart from that, background information is gathered. The geometry of the background might not be actively calculated in most cases, but it is still stored and acts as a physical context from which further information about the object of interest might be derived.

Therefore, primarily **geometrical** (shape and position of points), but also **semantic** (interpretation of photographs) and **temporal** (either as a “snapshot” in time or as a maintained photographic record) **types of information** are the resulting outcome of an investigation by means of Photogrammetry. To put it shortly, both **quantitative and qualitative data** are the results of a photogrammetric documentation.

Benefits of photographic documentation (with relation to human experience)

- Snapshot: Capturing of the 4rth dimension, hence allowing the study of it. In specific, ideal for studying dynamic phenomena that evolve in time, such as floods, wildlife populations, traffic, oil spills, forest fires.
- Record: Sharing with a greater audience of otherwise fleeting and personal sensory input, in the form of physical or digital data. Furthermore, the data is available for comparison, analysis and study.
- Broadened spectral sensitivity (compared to human eyes): with parts of invisible UV and infra-red spectrum (0.3-0.9μm as opposed to 0.4-0.7).
- Increased spatial resolution (compared to human eyes): with more powerful lenses and larger projection planes.

> Comparison with other methods of geometrical documentation

Optical methods using light as the information carrier lie at the heart of non-contact 3D measurement techniques[24]. Most of these entail triangulation techniques for the estimation of 3d point coordinates, hence share common traits and notions.

Reality-based* 3D Model Acquisition	
Non-contact methods based on light waves	
Active Methods	Passive Methods
Angle Measurement / Theodolite	Image-Based [Single | Stereo | Multi-Image Photogrammetry]
Laser Scanning	
Structured Light	
Focusing Methods	
Shadow Methods	
** as opposed to Computer Graphics*	

24 Luhmann, T. et al, “Close Range Photogrammetry”, 2006, Whittles Publishing

Of all the range of available options, photogrammetry is compared below to the most common alternatives, namely traditional topographic surveying and laser scanning. On the other hand, each project's details and needs will guide the selection process of the most appropriate method. Below, we are trying to estimate the comparable advantages of photogrammetry.

To traditional topography:

3d Scanning and Photogrammetry are both nowadays alternatives and, in a way, supplements to traditional topography methods that offer the same level of accuracy alongside with many other benefits. Most important are:

- **Speed of Data Acquisition** (time spent on field or with occupation of the object of interest)
- **Speed of Data Processing**
- **Texture Generation alongside 3d Model Acquisition**
- **Full rather than selective Documentation** (ideal for complex shapes)

Negative issues include the need for management of generated large amounts of data, the evaluation of the accuracy of the output, the estimation of errors due to improper photographic capturing and/or computing algorithms.

To scanning methods:

Currently, there are two main types of non-contact systems based on light-waves used to obtain 3D measurements: **active sensors** (laser scanners) and **passive sensors** (photogrammetry).

After recent developments, image based documentation (photogrammetry) stands as a proven and affordable[25] alternative to scanning techniques with comparable quality of results. For detailed information, see "Comparison of laser scanning, photogrammetry and sfm-mvs pipeline applied in structures and artificial surfaces" (D. Skarlatos & S. Kiparissi)[26]. The conclusion of the aforementioned research showed that Image Based Modelling (IBM) has an advantage over Terrestrial Laser Scanning (TLS) for small & medium-sized objects and distances in terms of methodology and accuracy.

More specifically, photogrammetry adds the following positive aspects[27] while maintaining comparable qualitative results with scanners:

- **Low Cost Equipment**
- **Easy & Lightweight to Transport**
- **Accessibility to non-experts** by means of automated software

** Collaboration of photogrammetry & laser scanners*

Sometimes, scanning and photogrammetry are not competing methods but are combined in a unified workflow, for example in cases where the surface area/3d model has been acquired by means of a laser scanner and the texture by means of photogrammetry.

Concluding:

We can sum up the following properties of Photogrammetry, when compared with respective methods of geometrical documentation: **accuracy, speed** (including time spent on field)**, affordability, openness, flexibility**.

> Through its unique strong-points:

Although typically photogrammetry can be employed in any project, the full benefits of such an approach are enjoyed when the subject under investigation has some of the following attributes:

25 "Falkingham (2012) found that even a camera with only 8 megapixels allowed him to produce models with an accuracy significantly better than 0.3 mm." JPT №12 - Journal of Paleontological Techniques

26 ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume I-3, 2012, XXII ISPRS Congress, 25 August – 01 September 2012, Melbourne, Australia

27 Skarlatos, D. & Kiparissi, S. (2012) «Comparison of laser scanning, photogrammetry and sfm-mvs pipeline applied in structures and artificial surfaces» ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume I-3, 2012, XXII ISPRS Congress, 25 August – 01 September 2012, Melbourne, Australia

- Out of human-convenient scale: either enormous or tiny[28]
  Example: landscapes, molecules
- Unable to reach due to physical limitations or unapproachable[29].
  Example: remote earth locations, planetary bodies
- Un-allowed to touch due to physical limitations.
  Example: fluids, particle-groups
- Unable to see with human vision (disregarding scale).
  Example: images as a result of sensors of various technologies and sensitivities (infrared,X-ray,etc).
- Un-allowed to touch for preservation reasons
  Example: most cultural heritage items, fragile natural formations
- Too complicated shape, heavy textured or heavily detailed, hard to define geometrically
  Example: biological/organic forms
- In the past[30]
  Example: destroyed structures or landscapes
- In motion/change
  Example: movable targets such as natural phenomena or animal/swarms, or in high speed transformation processes, such as crash test/deformations.

28 At the extreme, scanning electron microscope (SEM) photographs can be employed to create models at nanometer resolution (Piazzesi, 1973; Kearsley et al., 2007)
29 In this case, the source material is collected/gathered by means of remote sensing systems, such as aerial or satellite photography, UAVs (Unmanned Aerial Vehicle), etc.
30 An exciting example of photogrammetric modelling in paleontology from old images is the reconstruction of the famous Paluxy River sauropod and theropod dinosaur trackways from 12 photographs taken in 1940 (Falkingham et al., 2014).

APPLICATIONS OF CLOSE-RANGE DIGITAL PHOTOGRAMMETRY

The applications of close-range photogrammetry are varied and steadily expanding. A rough categorization of the contemporary application fields is presented:

Architecture & Civil Engineering	Geo-sciences & Surveying
Cultural Heritage Preservation	Natural Science Research
History-Related Science Research	Entertainment/Creative Industry
Industrial Metrology/Quality Control	Art
Law Enforcement/Forensics	Education
Healthcare / Medical	DIY/Constructions

A more detailed categorization of mainstream applications follows[31]:

Architectural photogrammetry	architecture, heritage conservation, archaeology
Engineering photogrammetry	general engineering (construction) applications
Industrial photogrammetry	industrial (manufacturing) applications
Forensic photogrammetry	applications to diverse legal problems
Biostereometrics	medical applications
Motography	recording moving target tracks
Multi-media photogrammetry	recording through media of different refractive indices
Shape from stereo	stereo image processing (computer vision)

A list of exemplary applications of close range digital photogrammetry in various fields:[32]

Automotive, machine and shipbuilding industries
- Inspection of tooling jigs
- Reverse engineering of design models
- Manufacturing control
- Optical shape measurement
- Recording and analysing car safety tests
- Robot calibration

Aerospace industry
- Measurement of parabolic antennae
- Control of assembly
- Inspection of tooling jigs
- Space simulations

Architecture, heritage conservation, archaeology
- Facade measurement
- Historic building documentation
- Deformation measurement
- Reconstruction of damaged buildings
- Mapping of excavation sites
- 3D city models

31 Luhmann, T. et al, "Close Range Photogrammetry", 2006, Whittles Publishing
32 ibid

Engineering
- As-built measurement of process plants
- Measurement of large civil engineering sites
- Deformation measurements
- Pipework and tunnel measurement
- Mining
- Evidence documentation

Medicine and physiology
- Tooth measurement
- Spinal deformation
- Plastic surgery
- Motion analysis and ergonomics
- Microscopic analysis
- Computer-assisted surgery

Forensic, including police work
- Accident recording
- Scene-of-crime measurement
- Legal records
- Measurement of persons

Information systems
- Building information systems
- Facility management
- Production planning
- Image databases

Natural sciences
- Liquid flow measurement
- Wave topography
- Crystal growth, etc.

It is obvious that a detailed presentation of examples for each field/discipline is beyond our scope. For detailed case-studies, the interested reader can search the publications of the **ISPRS - Commission V working group**, which deals -amongst other- with close-range photogrammetry applications in the field of industrial metrology, cultural heritage, architecture, biomedical & Geo-sciences.

It is worth to note that it is not by luck that the primary application of photogrammetry (other than surveying/map-making) was for the documentation of **Cultural Heritage Monuments**. Most of the International Conventions concerned with Cultural Heritage (e.g. Venice Charter, Granada Convention etc.) specifically mention the absolute necessity of a thorough geometric documentation before any kind of intervention to the monuments[33]. Photogrammetry is valuable throughout the whole process: from conservation and preservation of monuments to the communication of their cultural value to the public.[34] Many organizations and associations are actively engaged in this process, most notably European funded efforts, such as CARARE project[35]-part of the Europeana Effort[36], 3D Icons, Athina, etc. One of the important trends in this field is the distribution of the 3d content to a wider audience in a meaningful way. The following quotes from the blog of the British Museum are very illustrative of the future course towards a **virtual museum**[37]: “With the help of the 3D models created from scans, we have the potential to develop interpretative media

33 Prof. Andreas Georgopoulos, 2015, CULTURAL HERITAGE PHOTOGRAMMETRY, Innova, Virtual Archaeology International Network
34 Klaus Hanke & Pierre Grussenmeyer, “ARCHITECTURAL PHOTOGRAMMETRY: Basic theory, Procedures, Tools” Corfu, September 2002, ISPRS Commission 5
35 http://www.carare.eu/
36 http://www.europeana.eu/portal/
37 http://blog.britishmuseum.org/tag/photogrammetry/

in the galleries, online and through mobile and wearable technology. There are many potential approaches, from delineating the carved scenes where the stone has deteriorated to reconstructing the original architectural scheme, complete with colour paint and torch-lit ambience as they might have appeared to the Assyrians in their original setting...Computer 3D technology is being increasingly adopted in museums to aid with conservation, curatorial research and interpretation.... the British Museum now has over 1.2 million images of objects in the collection online..... It doesn't take much to imagine a time when 3D scans become the de facto method of recording objects in the collection."

In **architecture & civil engineering**, photogrammetry is applied not only to cases of cultural significance (to yield virtual models of historical buildings or help in restoration projects based from archived photographs) but also to common practical issues of **documentation of built environment** for renovation, restoration and alteration/re-use purposes.

In civil engineering structures (buildings & infrastructure), photogrammetry finds applications such as measuring of deformities for further use in static analysis in cases of damage, deterioration or simple maintenance[38]. Issues that can be tackled include stability evaluation of structures, slope failure prediction, displacement measurement, monitoring of dams and in general, the **monitoring of dynamic processes**.

Similar monitoring processes can be found even in the field of agriculture, i.e. for the estimation of leaf area index as part of crop monitoring[39].

Scientific history-related fields such as archaeology[40], paleontology[41] and even anthropology benefit from photogrammetry with typical applications such as documentation of the digging site, the excavation progress and the exact geospatial relationship of the findings. The acquired information can be used to create a digital archive for research, storing, sharing and displaying purposes. The production of digital models from specimens offers the important benefit of facilitating the dissemination of data and allowing for widespread collaboration. A result of this is the emergence of **digital, online repositories**. Furthermore, working with the digital models offers greater flexibility than handling the actual physical object. Even more, the resulting digital reconstructions can be compared or further analysed (with finite element analysis) in order to advance scientific theories and test hypotheses, something otherwise impossible. Examples of this include the digitisation of skeletons that has enabled researchers to investigate ranges of motion and explore aspects of biomechanics (i.e. locomotion and feeding) in extinct animals, by applying constraints and forces on the digital models to produce simulations. Another example from this field is the major renaissance of palaeoichnology (the study of fossil traces) in recent years: in this case, photogrammetry offers a definite solution, since on site access/field work can be difficult to impossible, access time limited and under restrictions, the traces can be subject to sever weathering and erosion, etc.

Similar **comparison and analysis of digital models** can be found in medical applications for the tracking of deformities & establishing diagnosis.

Applications can be found in any environment - where light can travel and a sensor device has been developed to withstand the conditions. Some demanding applications in these terms take place in underwater environment and might involve scenes with cultural or historical significance, such as shipwrecks, but also extend to natural habitat and wildlife research, as well as the monitoring of man-made constructions and pipeline networks.

Photogrammetry is also ideal for use in natural wildlife research, since it allows for the acquisition of metrical data while avoiding a **close-range/contact approach**, which in many examples in unwanted or impossible. Examples include observing wild life subjects in their native environment, such as measuring sperm whales at sea[42] or the movement of flocks and swarms.

38 Carneiro da Silva, D., "SPECIAL APPLICATIONS OF PHOTOGRAMMETRY", Chapter 4, Application of a Photogrammetric System for Monitoring Civil Engineering Structures, 2012, InTech

39 "Application of close-range photogrammetry and digital photography analysis for the estimation of leaf area index in a greenhouse tomato culture", International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XXXVIII, Part 5

40 http://archphotogrammetry.com/
http://www.archaeologicalgraphics.com/photogrammetry/
http://www.archeos.eu/#what-is-archeos

41 https://dinosaurpalaeo.wordpress.com/my-publications/
http://www.jpaleontologicaltechniques.org/pasta3/JPT%20N12/Bulletin.html
Falkingham, P.L. 2012. Acquisition of high resolution three-dimensional models using free, open-source, photogrammetric software
Cunningham, J.A. et al, 2014. A virtual world of paleontology
Mark Sutton, Imran Rahman, Russell Garwood-Techniques for Virtual Palaeontology-Wiley-Blackwell (2014)

42 «Growcott, A.; Sirguey, P. & Dawson, S. (2012), 'Development and assessment of a digital stereo photogrammetric system to measure cetaceans at sea', Photogrammetric Engineering and Remote Sensing 78(3), 239-246.» by the Department of Marine Science at the University of Otago, New Zealand

A good example where photogrammetry acts as a method of **fast spatial documentation** is by the law enforcement agencies in cases of car crashes[43] and the models can be further used for reconstruction purposes with suitable software. In the field of forensics, photogrammetry can be used to acquire 3d models of faces and bodies that can be compared for person identification purposes. For surveillance and security purposes, photogrammetry can be applied on still images taken from CCTV cameras for crime investigation.

Less wide-spread but quite interesting are applications in art, such as custom-made jewellery shaped to fit on human subject after acquiring a 3d model of the body’s surface[44].

An important emerging application is that in the creative/entertainment industry for the creation of **digital assets** for the film industry, TV commercials, for videogame development[45] and general digital arts. There is certainly no highway open to photogrammetry as an alternative to traditional 3d modelling & rendering for the creation of digital assets. Manual «hand» modelling or even procedural modelling has a great deal of many advantages related to the behaviour of the assets and general resource management, which directly affect the performance of the rendering or game engines in terms of speed and bugs. But photogrammetry is on the onset to be regarded as a valid, new tool in the toolbox of an indie and adventurous/exploring creative studio.

43 https://www.policeone.com/police-products/accident-reconstruction/articles/1735153-Close-range-photogrammetry-for-crash-reconstruction/
http://www.hg.org/article.asp?id=5220

44 http://jazztdesign.com/post/10604010277/made-on-you

45 Up to now the list of video games that have incorporated photogrammetry has grown to quite a few important names in the industry, such as Metal Gear Solid V, Halo 4, Cyberpunk 2077, Talos Principle & Ryse: Son of Rome / War Thunder.

ON THE HISTORY OF PHOTOGRAMMETRY

When presenting an applied science, a historical overview of its evolution is fundamental for a deeper understanding of the subject. Therefore, some historical facts are offered that show how the character, scope & methods of the discipline changed over the course of the years.

Evolution cycles of technologies

There is a simple concept that describes the evolution of technologies and it follows life's growth cycle of birth, growth, maturity, decline and death[46]: The "turn of each wheel" is brought about by a basic invention each time. Within each cycle, we note the following transitions, presented in more detail:
- first practical instrumentation of invention
- assimilation of invention and application to normal practice
- maturity / prevalence
- transition to next cycle/coexistence with competitive innovations

Whatever the field, there is always a technological gap between the latest findings in research on one hand and the implementation of these results in manufactured products and their use in industrial process on the other. The time in between is a transition period, where established practises that have been optimized in the years before exist side-by-side with emerging, more powerful but yet un-tested methods.

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4 stages in history of PG evolution

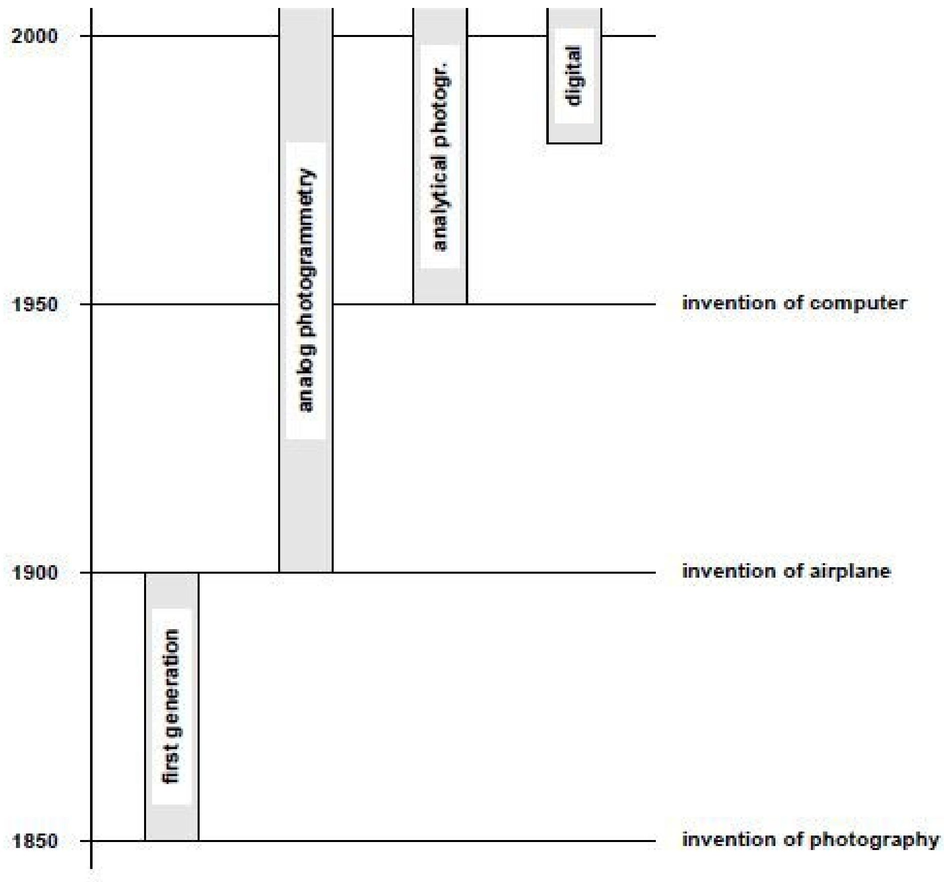
We can distinguish 4 stages in the life-cycle of PG by now[47], set off by improvements in the involved technologies:
**Every phase of course is overlapped with the next for a considerable amount of years (15-20).*

1850 - 1900		(ending ca. 1930)
I.	**Plane Table photogrammetry**	graphical evaluation
1900 - 1960		(ending ca. 1980)
II.	**Analogue Photogrammetry**	analogue sensors & analogue images optical-mechanical photogrammetric instruments (stereophotogrammetry)
1960 - 1980		(ending ca. 1990)
III.	**Analytical Photogrammetry**	analogue sensors & analogue/digital images, optical-mechanical & digital photogrammetric instruments (stereophotogrammetry)
1980 -		present
IV.	**Digital Photogrammetry**	digital sensors & digital images Computer (multi-image photogrammetry)

** In photogrammetry the word "Analytical" has been used synonymously with "Computational", where the solutions are obtained by mathematical methods as against "Analog", where solutions are obtained by analo-*

46 The division of a technology's evolution in development cycles is based on the economic theory of Kondratjew.
47 Konecny, G. (1985) «The International society for Photogrammetry and Remote Sensing- 75 years old or 75 years young» Keynote Address, Photogrammetric Engineering and Remote Sensing, 51(7), 919-933.

gy or similitude developed through optical-mechanical procedures.[48]



Major photogrammetric phases as a result of technological innovations[49]

Components & Parameters	Stages of Development in Photogrammetry		
	Analogue	Analytical	Digital
Input	Analogue	Analogue	Digital
Model	Analogue	Analytical	Analytical
Output	Analogue	Digital	Digital
Degree of Hardness	3	1	0
Degree of Flexibility	0	2	3

The characteristics of three stages of photogrammetry[50]

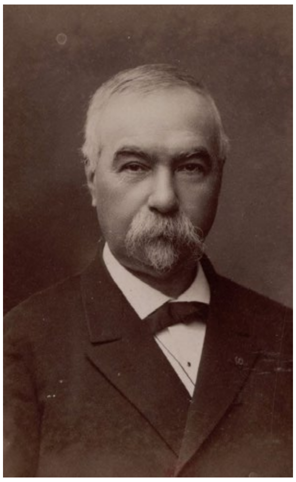
The Birth of Photogrammetry

The invention of photography during the 1830s and 1840s by Fox Talbot in England and Niepce & Daguerre in France triggered the concept of photogrammetry[51]. Indeed, shortly after, by the middle of the 19th century, the necessary elements from the fields of mathematics, optics, photography and topography

48 History of photogrammetry, Chapter 6: analytical methods and instruments, Sanjib k. Ghosh, professor of photogrammetry, Laval university, Canada, Commission VI
49 T. Schenk, Introduction to Photogrammetry / GS400.02, Ohio State University, 2005
50 Zhu, Qing & Chen, Jun (2007) “The Photogrammetry Education for Multidisciplinary Geomatics in China”, ISPRS Highlights.
51 As early as 1840, Argo, Director of the Paris Observatory advocated the use of photography for topographic surveying.

were available, so that photogrammetry could be created out of their ingenious unification[52]. This "ideal timing" is also evident by the fact that for photogrammetry's birth, we can name not one, but 2 leading figures who operated separately but with similar focus in mind, around the same space-time (central Europe of mid 19th century): **Aimé Laussedat** in France & **Albrecht Meydenbauer** in Germany. Aimé Laussedat is generally accepted as the "father of photogrammetry" for his manifold contributions, while Albrecht Meydenbauer is another important pioneer in this field, who invented the principles of photogrammetry in 1858 independently from Laussedat and developed methods and instruments especially for architectural photogrammetry and the documentation of cultural heritage objects.

1850-1900: Plane Table photogrammetry[53]



Aimé Laussedat (1819-1907): French military officer, charged with map-making & surveying duties for the French government.

Aware of the shortcomings of the established surveying techniques, Laussedat showed interest in previous, experimental approaches of surveying by using hand-drawn sketches[54]. He clearly saw the limitations in accuracy of hand-drawn depictions and found that light-drawn images, as those created by the camera obscura/lucida device, had greater reliability for his intended purposes. Aware of the recent inventions and trends of his time, Laussedat acquiring a **camera lucida** model by W.H. Wollaston, which he put in use in 1849 for the documentation of the facade of the Hotel des Invalides in Paris. After this initial success, another documentation project followed in Vincennes's fortress in 1850. Laussedat's innovation was to place a modified version of the camera lucida on the traditional surveying plane table. The goal was to make accurate sketches from the locations of the established network instead of angle and length measurements. Since the perspective images could be used later as reference, he transformed the angle measurement process from **field work** to **office work[55]**. Thus, we can claim an emergence of photogrammetry, even preceding the invention of photography with fixed latent image. In later years of course, Laussedat moved on to use photographic cameras on map-making projects[56], as well as experimented with kite & balloon photography.

Albrecht Meydenbauer (1834-1921): German architect working as a building surveyor of the Prussian government. On one of his first assignments on 1858 about the documentation of the cathedral in the city of Wetzlar, he conceived the idea of documentation of buildings through photography. His primary motivation was to avoid the conventional, often dangerous, manual method of measuring facades. Soon though, he realised the potential of using photogrammetry for the creation of a cultural heritage archive of architectural monuments as a means of pre-emptive protection against destruction and deterioration. He exposed his ideas to the curator of cultural heritage in Prussia hoping for government support.

He described how photographic images can store the object information in great detail and with high accuracy, which can be further used for geometric measurements and developed graphical methods for the production of plans of building facades.

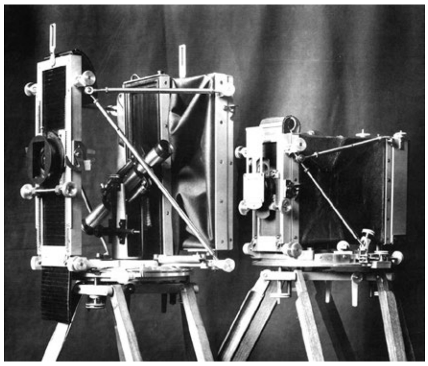
52 It is interesting to note though that theoretical concepts of photogrammetry (central projection) had an even older root in time and came from pictorial (pre-photographic) fields of interest. It allowed the use of graphical methods rather than mathematical calculation and could be used by those with less education than other instruments.

53 According to Konecny, plane table photogrammetry is an extension of the conventional plane table surveying.

54 In 1725, Swiss M.A. Cappeler used a supportive device, similar to the aforementioned one, to create accurate sketches of mount PIlatus from two separate locations and managed to estimate the height by means of triangulation. Thus, a photogrammetric type of project was completed without a single photograph but rather with the creation and use of "scientific" (instead of artistic), geometrically accurate sketches!

55 Conventional surveying was used to locate the position of the cameras and a few control points in the scene being photographed. Each exposure station was determined by resection and plotted on the plane table. The exposed photos were oriented on the plane table. Directions from ground control points were graphically plotted from the imagery. Finally, the directions to the different objects were transferred onto the map sheets.

56 At the Paris Exposition in 1867, Laussedat exhibited the first known phototheodolite and his plan of Paris derived from his photographic surveys.


Camera by Albrecht Meydenbauer, 1870

Meydenbauer made important contributions to the development of suitable instruments for photogrammetric purposes. Given that his underlying concept was correct, the shortcomings of commercial cameras available at the time made it evident that for trustworthy results, new equipment needed to be developed. Meydenbauer felt the need for a photographic camera that could be relied on as a measuring instrument.

Since he noted the fact that building documentation more often than not required wide-angle lenses, his first instrument, built in 1867, the **Pantoskop**, was fitted with a **wide-angle lens** (105°) from the optical workshop of Emil Busch in Rathenow and had a **focal length** of 25 cm & a **image format** of 30X30 cm. Glass plates were used to carry the light-sensitive emulsion. This camera was very shortly after put to experimentation.

In this early experimentation, we can already note the basic elements of a **metric camera**, as would later be developed:
- **Defined Image Plane** by fixing the image plate on a mechanical frame before exposure or by the use of glass plates
- **Realised Image Coordinate system** by positioning of cross-hairs during exposure
- **Fixed focus** with known focal length in order to define a single, uniform principal distance through all photographs
- **Mounting of the photographic camera** on a tripod with the possibility to adjust the camera axis and the image plane

Following experimental devices were equipped with higher focal lengths (35cm, 53cm) and a larger image format, i.e. 40X40 cm. Large formats were desirable because they allowed for **higher resolution** in the restitution process, which was completed graphically (reaching accuracy of 0.2 mm in real world dimensions).

* It is interesting to note that Photogrammetry is born with a close relationship to **Architecture** & **Cultural Heritage**. For at least the first fifty years of active photogrammetric use, the predominant application was to close range, architectural measurement rather than to topographical mapping. By virtue of their regular and distinct features, architectural subjects lend themselves to this technique. The pinnacle of this understanding was Meydenbauer's vision of the "Denkmälerarchiv" (Cultural Heritage Archive): an archive of heritage objects, recorded in metric images in such a way that they could be reconstructed in cases of destruction or degradation. His idea become realised in 1885 by the founding of the Royal Photogrammetric Institute of Prussia, where he was positioned as directing manager. Between 1885 and 1909, Meydenbauer compiled an archive of around 16.000 metric images of the most important architectural monuments, which is still partly in existence today.

Next stages of development: instruments

Italian Ignazio Porro (1801-1875) was another important contributor to the early stages of photogrammetry. He was the inventor of **tele-lens,** as well as the creator of a photographic camera for panoramic photo-shootings (1858), in which he used spherical image plates and a spherical lens (the field of view was defined mechanically). This setting allowed for decreased lens-induced aberrations, high quality and reliable metrical data. To make up for the difficult measurements on the spherical image plates, Porro further designed a system called "**Photogoniometer**", which was the basis for further development in future analogue photogrammetric machines[57].

Porro, as well as Paganini in Italy, in 1865 and 1884 respectively and later in 1896 Koppe in Germany, further developed the metric camera by combining it with a theodolite for recording angles/directions in space, thus creating an instrument, aptly named "**Phototheodolite**[58]**".**

The next hallmark in instrument development was the creation of the **stereocomparators**, instruments

57 Later known as the Porro-Koppe Principle: "The system for elimination of known camera lens distortion by observing the photograph (or projecting it) using a lens with the same distortions as the camera". (https://definedterm.com/)
58 http://www.sage.unsw.edu.au/currentstudents/ug/projects/f_pall/html/t13.html

that allowed for stereoscopic viewing of the photographs and direct measurements of 3d points.

At its root, this step was made possible by the understanding of the rules of stereoscopic viewing, that were developed by Sir Charles Wheatstone and amounted to the creation of his “Stereoscope”, patented in 1838. Wheatstone’s experiments on stereoscopic viewing had started with drawn sketches and precede the invention of photography. The rules thus discovered were later passed on to photographic capturing of images suitable for stereo-viewing. Stereoscopes (also, stereopticons or stereo viewers) were made popular by Oliver Wendell Holmes long after, around the 1880’s, which is exactly the era when the first photogrammetric stereo-comparators emerged.

The step from stereo-viewing to stereo-measurements was made possible by the invention of the **floating mark** by F. Stolze in 1892. Carl Pulfrich in Germany and H.G. Fourcade in South Africa, working independently and almost simultaneously, worked on the practical application of Stolze’s discovery (1901) and developed instruments for measuring and deriving spatial dimensions from stereo-photographic images using floating marks. The measurements were made point by point and their 3d space coordinates were calculated analytically (by solving the algebraic equation of the intersection of their corresponding rays).

Next stages of development: analytical methods

An important contributor on this field was Ernst Abbe, the co-founder of the German Zeiss Works, who in 1871 started intense studies and tests for optical elements (lenses) on the basis of rigorous mathematical analyses.

German mathematician G. Hauck established in 1883 the relationship between projective geometry and photogrammetry, analysing how 2 perspectives depictions of an object can lead to the calculation of a third. This should be considered as a most fundamental geometric concept and the basis of most classic analytical photogrammetric developments.

In the same line of thought, Sebastian Finsterwalder (1862-1951) in a series of publications during 1899 to 1937 established a very strong foundation for analytical photogrammetry. In these he brought about the geometric relations which govern **resection** and **intersection** as well as relative and absolute orientations.

1900-1960 Analogue Era

After the research and developments of the previous era, the required maturity and practicality had been achieved for the **widespread use of photogrammetry** for surveying purposes thanks to use of the stereo-comparators. By the 1930’s, Collier presents photogrammetry “as a proven technique for accurate map-making, used mainly by the military during war-situations, colonial occupation forces, country’s own governance”[59]. Indeed, at that time, non-topographic use was sporadic, since few suitable cameras were available and analogue plotters imposed severe restrictions on principal distance, image format and disposition and tilts of cameras. It was around the 1930’s that instruments, such as the Stereoplanigraph C5, became available that were able to use oblique and convergent photography, allowing for less rigid photographic requirements.

This era’s main characteristic is the development of aviation and the mounting of metric cameras on airplanes gave rise to **aerial photogrammetry**[60]. Aerial photogrammetry proved an important new tool in map-making for military purposes during the World Wars and its widespread application and importance gave a very significant boost to photogrammetry’s evolution. Aerial photogrammetry was especially successful since the earth photographed vertically from above proved an almost ideal subject for the photogrammetric method given the processing capabilities of the time.

Processing Methods

The main characteristic of this era was the firm establishment of an analogue approach to the fundamental photogrammetric questions. This meant the creation of heavy, **specialized optical-mechanical devices**

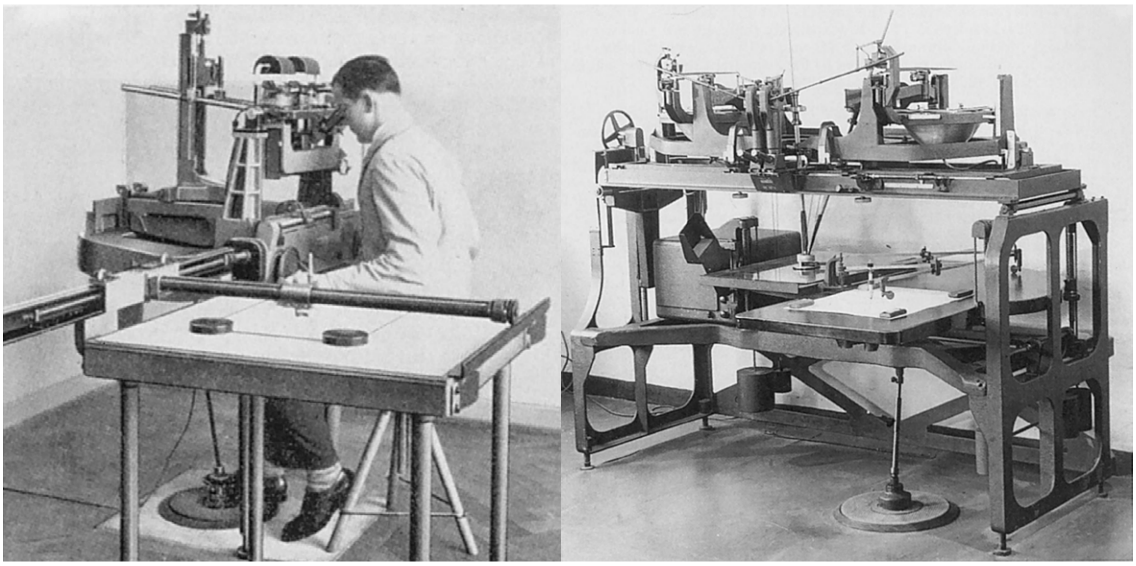
59 Collier, O. (2002), “The Impact on Topographic Mapping of Developments in Land and Air Survey: 1900-1939”, Cartography and Geographic Information Science, 29(3): 155-174.

60 More on this, BBC documentary ‘Tomorrow’s World’ explores the scientific feat of aerial photo mapping, original airing 1970. http://www.bbc.co.uk/archive/aerialjourneys/5320.shtml

that could be used to solve the basic geometrical problems. The tendency was to avoid calculations as much as possible and exploit the benefits of stereoscopy.

Photogrammetric Instruments

The photogrammetric instruments can fall in two rough categories: the first revolves around the rectification of a single photograph with the intention to retrieve an orthophoto (as mentioned, a photograph of an object that can provide reliable metrical information, given of course the limits of the image’s resolution/ scale, as it was defined at the moment of capture). A machine such as this was called a **rectifier**- it could perform the transformation from central projection to orthogonal projection in an analogue fashion. The second revolves around stereophotogrammetry and the ability for 3d point restitution: the **stereoplotter**, also called an **analogue plotter**. The measuring instrument for measuring actual photo coordinates on a diapositive was called a **comparator**.



Wild A4 (1933) for terrestrial photogrammetry (left) and Wild A5 (right), important instrument for WWII (1937)

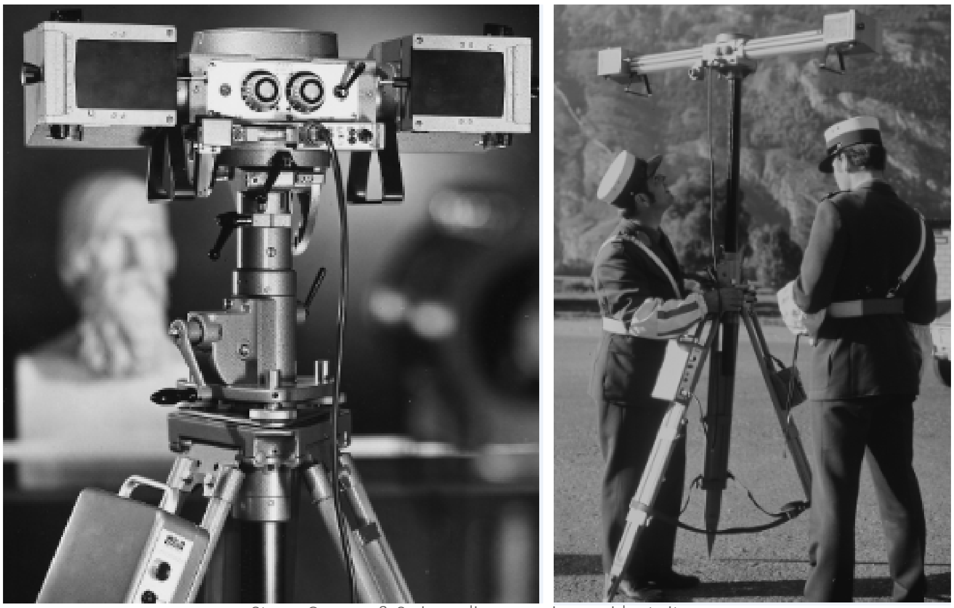
The two leading companies of photogrammetric equipment of those times are active up to present day: Leica (a merger of the former Swiss companies Wild and Kern) and Carl Zeiss of Germany (by unification of Zeiss Oberkochen and Zeiss Jena).

Photographic Sensors

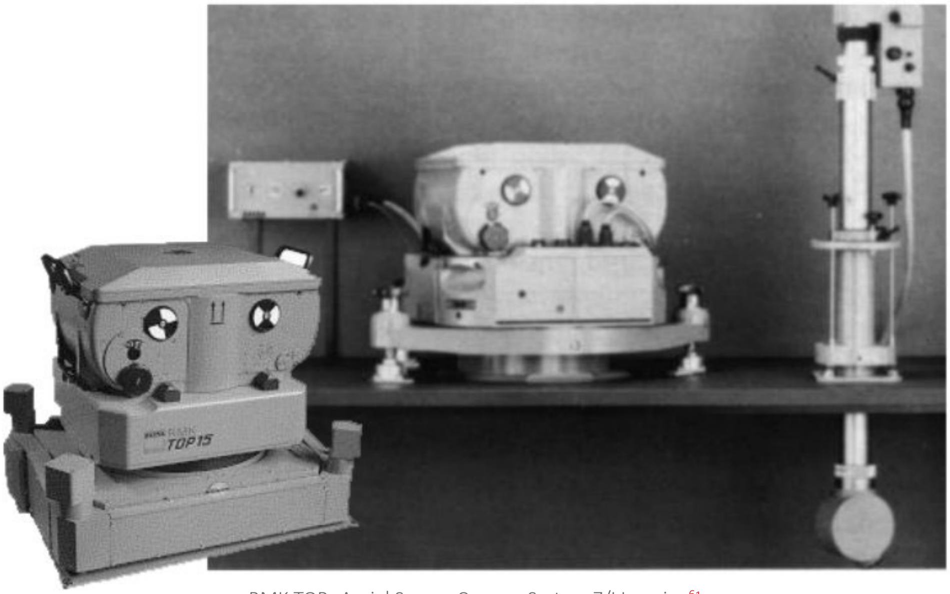
During this era, specially developed, **metric cameras** were used. These cameras exhibit the same properties with those of Meydenbauer but within higher results in precision, resolution and image quality. Of course, **analogue film** was used to capture the images and printed in paper.

Of course, the majority of interest received the **aerial metric cameras**, since they were the most demanding sensor instruments in terms of performance and capabilities.

Another invention of the time was the **stereometric camera**. It comprises of two identical metric cameras fixed to a rigid base of known length and such that their axes are coplanar, perpendicular to the base and, usually, horizontal. This facilitates the capturing of stereo-pairs given adequate base from subject.



StereoCamera & Swiss police mapping accident sites.



RMK TOP- Aerial Survey Camera System Z/I Imaging[61]

1960-1980 Analytical Era

Given the emergence of the computer, new interest in the analytical formulation of the photogrammetric problems arose. According to this approach, the relation between image points and object points is described through **numerical calculations** based on collinearity equations. It was understood that these algebraic equations could now be processed in great speed with the employment of the computer, rather than the human mind and hand. Thus, the analytical approach, given time and effort, seemed to show greater potential for the facilitation of the photogrammetric process, as opposed to the already established, analogue one (which in its own terms was a significant improvement over former methods). Since the calculations involved were performed by the computer, analytical photogrammetry is also referred to as “computational” photogrammetry.

Processing Methods

The first analytical attempts were applied to photogrammetric triangulation. Seminal papers by Hellmut

61 www.geog.ucsb.edu

Schmid (1956-57, 1958) and D.C. Brown (1958) laid the foundations for theoretically rigorous **block adjustment**. Schmid was one of the first photogrammeters who had access to a computer and developed the basis of analytical photogrammetry in the fifties, using matrix algebra. Brown developed the first block adjustment program based on bundles in the late sixties. The developed algorithms introduced the method of bundle adjustment for the orientation of the block, whereas in the previous years the method of “independent models” was the norm. Bundle adjustment resulted in 3d point determination with simultaneous orientation of the photographs and taking camera parameters into account[62]. Thus, calibration and restitution were performed in one process. Bundle adjustment proved of vital importance, especially to close-range applications, since it imposes no restrictions on the positions or the orientations of the cameras.

Photogrammetric Instruments

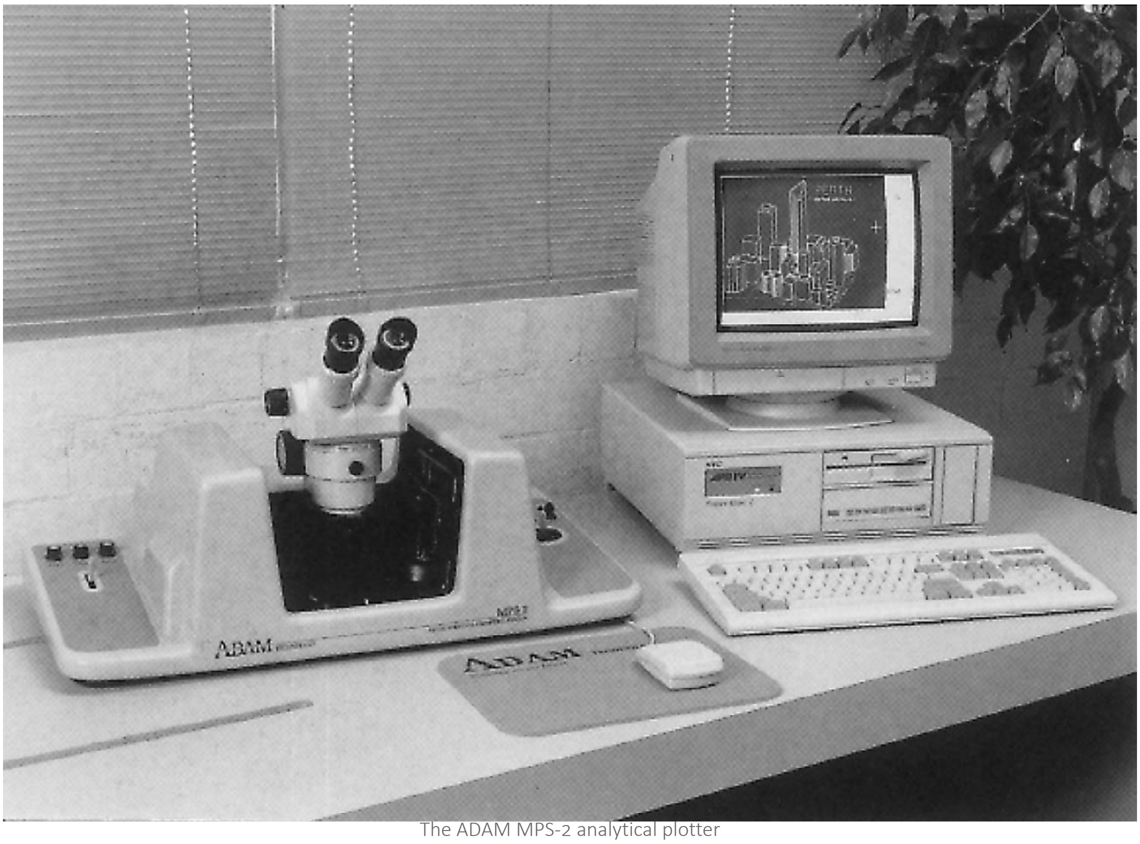
The pioneering idea of Helava was to merge computer and stereo-plotting instrument, resulting in **analytical stereo-plotters** (also known as 3d digitizers) with fully numerical reconstruction of the photogrammetric models. Helava built the first analytical plotter, the US-1, in the late fifties. In 1964, Bendix/OMI produced the first commercially available analytical plotter, the AP/C. These instruments became available on a broad base around the 70’s.

At first, existing stereo-plotters were equipped with devices to record coordinates for input to electronic computers for further analytical processing. This stage was referred to as semi-analytical. Later on, fully equipped analytical stereo-plotters were introduced, including refined machinery that could register co-ordinates with linear and rotational impulse counters and employed servo-motors for detailed control and report of point-positions.

Photographic Sensors

In this era, the photographic input is still analogue using film and printed diapositives. Important developments were made in the field of aerial metric cameras. There are significant improvements on lenses and stability of interior camera geometry, as well as film flattening devices using pneumatic methods. Aerial metric cameras were further modified to adjust to each flight planning and execution based on aircraft speed and overlap percentage. There is also the emergence of GPS tracking that could further assist the accuracy in the orientation process.

62 Calibration via bundle adjustment is usually known as self-calibration



The ADAM MPS-2 analytical plotter


Analytical Conversion of Wild B8 stereo-plotters

1980-present Digital Era

Procedures in which both the image and its photogrammetric processing are digital are often referred to as digital photogrammetry. At the first stages (but also later on), scanning of analogue photos was used as input for the digital processing. Important breakthrough was the development of opto-electronic image sensors since the middle of the 1980s, thus completing a full digital workflow. The definitive trait of the digital age, though, is the marriage with computer vision. The “portrait” of contemporary photogrammetry entails **automated processes**[63] of orientation with minimum human feedback, mainly involved with setting preferences that define the quality, accuracy & processing time.

Processing Methods

Primary digital work-flows were based on the established principles of stereophotogrammetry. In later stages, with the introduction of computer vision algorithms, the human parameter was decreased. Effort and research was invested in the automation of the entailed processes, namely, image matching techniques to extract tie points for bundle adjustment, the automatic generation of DTM/DSM[64] and the generation of orthophotos and orthophoto mosaics.

Photogrammetric Instruments

The descendant of the analytical stereoplotter is the **digital photogrammetric workstation** (DPWS), also known as **softcopy workstation**. Defined by the ISPRS in the late 80’s as the “hardware and software to derive photogrammetric products from digital imagery”, DPWS made their first appearance in the commercial world during the ISPRS Congress in Kyoto in 1988 and they were commercially available by the early 90’s.

The hardware requirements of such a station included a strong processing unit (at first using Unix and later on Windows operating system), a graphics-rendering card, a suitable screen for stereo viewing (and accompanying eye-wear), as well as input devices (such as specialized 3dimensional mouse designs for the extraction of x,y and z coordinates). In the early years, the setup for viewing included a screen with split projection of images and a stereo-viewing mask, as a natural evolution/reminder of analytical plotters. Later on with the development of new ways for stereo-viewing, the most common arrangement was the use of 2 screens, one for the User Interface (UI) and one dedicated to stereoscopic viewing with suitable goggles.

On the software level, a DPWS consists of four components: a data base level for vector/raster/attribute data, a level for image handling, compression, processing and display, a level of photogrammetric applications such as image orientation, the generation of digital terrain models (DTM) or “capturing” of vector data, and the user interface level.

The tasks performed at these platforms are image orientation, surface point restitution, generation of orthophotos and orthophoto mosaics and vector data capture. Intensive vector data capture is usually carried out in a CAD environment.

With the introduction of multi-view stereo workflow, the need for stereoscopic viewing slowly diminished. Nowadays, photogrammetric work-flows can be supported by personal computers without specialized accessories.

Photographic Sensors

The important new element at this stage is the introduction of digital sensors. Around the beginning of the 1990s, the CCD was introduced as an image sensor and the digital camera was the new photograph acquisition apparatus. Digital cameras were an improvement over analogue ones, due to the higher stability of their interior geometry and flatness of the image sensors, as opposed to analogue films. An additional benefit was the fact that the digital image format also enabled the potential for radiometric adjustments. Since the method of bundle adjustment was introduced and the parameters of interior orientation of all the cameras may be included as unknowns in the solution, it was no longer necessary to use metric cameras for high precision work. This event further opened the way for the adoption of non-metric digital cameras, which although lack the advantage of known and constant interior orientation, are usually less cumbersome and less expensive. Thus, metric cameras for close-range photogrammetry were abandoned.

The need for high quality metric cameras still exists in aerial photogrammetry mainly due to image sensor

63 Processes can be defined as automated if they are controlled by a list of parameters which need to be predefined by a human operator.

64 Digital Terrain Model /Digital Surface Model

size. The physical limitations of the digital sensor do not allow a large enough format that can compete with the resolution of 23X23 film formats of the past. Still, significant improvements on aerial digital cameras has been made, most notably the development of Three-Line-Scanner (TLS) Sensor System, which greatly enabled DSM extraction for urban landscapes.

Digital photogrammetric workstation ZEISS Phodis ST[65]

Important breakthroughs:

Real time applications

Instant feed of primary data, automation procedures and short processing cycles give digital systems a new trait, the possibility for complex real-time applications. This have proved critical to the widening of application range, in particular with reference to industrial metrology and robotics.

Interoperability with other software environments

A trend in close range photogrammetry is the integration or embedding of photogrammetric components in application-oriented hybrid systems. This includes links to packages such as 3D CAD systems, databases and information systems, quality analysis and control systems for production, navigation systems for autonomous robots and vehicles, 3D visualization systems, internet applications, 3D animations and virtual reality.

> Connecting with Semantic Information: bridging to GIS / BIM systems:

Out of the above, an important branch is the need for connectivity with semantic data, i.e. attribution of properties to geometrical data. As stated, there is an "increasingly important integration of photogrammetry with spatial information science"[66]. Thus, the step beyond plain geometry and colour is made, where the 3d model is treated as an "object" -in the sense of object-oriented programming- with defined and assigned attributes. This complex data structure can be further used in a wider context, such as subjected to spatial analysis in an GIS (Geographical Information Systems) or BIM (Building Information Model) environment. Examples of this are demonstrated as early as 1988 by the combination of Erdas' Imagine and ArcInfo from ESRI.

** > > For a thorough photographic archive of historical photogrammetric instruments, please visit here: http://www.wild-heerbrugg.com/photogrammetry1.htm*

65 https://www.researchgate.net/publication/277292465_Acquisition_of_CAD_Data_from_Existing_Buildings_by_Photogrammetry
66 Heipke, C. "Digital Photogrammetric Workstations - A review of the state-of-the-art for topographic applications", University of Hannover

EVOLUTIONARY FACTORS

Photogrammetry is a discipline that involves a wide range of knowledge from disparate fields - therein lies also the speed and extend of its transforming evolution in the past 200 years. Given about 200 years of history, we can set the recent 60 years apart, as those that have seen a more rapid and important technological increase.

As stated, photogrammetry receives the evolutionary forces of many other fields, most important of which have been:
- **Photography**
- **Aviation**
- **Computation/Digitization**
- **Electronics**

The current driving forces behind Photogrammetry’s evolution:

Sensors/Primary Data:
- Improvements in sensor’s technology, enhanced sensitivity and precision

Computational Hardware:
- Ever increasing computational power and speed with maximized portability

Algorithms/Software:
- Efficiency of the computer vision algorithms & automated software

> > > We note a **decrease** in the necessary effort, in terms of **time, expenses & expertise**.

Factors that affect in general the character of a photogrammetric project, from start to finish:
- New technologies and techniques for **data acquisition** (widening the scale of the target object from the enormous (astronomy) to the minute (nano-bio-technology), as well as the potential to acquire images from otherwise intangible or unapproachable targets.]
- **Data processing** (computer vision algorithms),
- Structuring and **Representation** (CAD, simulation, animation, visualisation)
- Archiving, Retrieval and **Analysis** (spatial information systems)

> > > We note a **widening of the capabilities** in every step of the workflow, starting with data input and ending with further analysis/implementations of the output.

NOTABLE CHANGES

In the current state, we note the following qualitative differences with the past use of photogrammetry:

Main application focus

If we cut the history of evolution short, from the original applications at the point of emergence of the discipline to the most recent innovative applications, we would maxim something like «from **map-making** to **metrology**».

Digital to Digital

The most important note would be the transition from a "**optic-mechanical equipment to a fully digital flow**". The important qualitative factor that arises from this is that the **digital thread**[67] continues from creation to final destination of the produced work.

A shift in User Groups

Following the division of the history of Photogrammetry into evolutionary stages, we can likewise note a gradual shift of the user groups from a very limited and highly specialized group of professionals to a more diverse crowd.

first line users:

military map-making, civil purposes - survey engineers

second line:

architects, geologists, geographers, cartographers, forest engineers, police, architects, archaeologist

third line:

>>> under exploration/**open to question**!

67 "Digital Thread ... is the idea of seamlessly integrating information through the value chain – from initial capability planning and analysis, through design, manufacturing, testing, and on to final sustainment and disposal phases – meaning that specialists throughout the process can work on the item simultaneously to inform decisions through the life of a system or product." Digital Manufacturing and Design Innovation (DMDI) Institute

FUTURE PROSPECTS

There is a definitive and gradual shift from the sealed sphere of the «**military**» use, to the closed, professional use in the «**civil**» world. We can expect a stage of «**social**», where the technology leaks into the world of productive industry, creative industry and educational institutions. The evolution’s ending stage comes with full assimilation in the «**cultural**» level, where by «cultural» we mean the actually «alive & lived» daily culture, in terms of peoples daily practices in everyday life, spontaneous and initiative experimentation.

The claim to a turning point

Photogrammetry can be seen at a **turning point**, entering the next stage in the technology’s evolution, which is the assimilation in the social level (even foreshadowing the cultural) in an era where the speed of transgression is unprecedented.

The claim to disruptive innovation potential

Such an opening typically is a period of time of high **innovative potential**, where new applications emerge. Some of the possible future paths, such as photogrammetry’s synergy with 3d printing, transcend the innovative potential and can go as far as to be proclaimed as “disruptive[68]” innovations, showing particularly high interest.

Factors that support the potential of a new wider user group

- Affordability/portability and wide-spread familiarity of high-quality **cameras** with the public
- **Automation** of procedure with minimum user input
- Increasing power and affordability of personal, private-use **computers**
- Networking and web-based applications as a means to amplify computational strength
- Open and free self-learning options through the **internet**, in forums and sharing communities
- A fully **digital output** that can be exploited as source material in a work-pipe for further modification/process

Conclusion:

The shift in a wider and untrained user group brings -together with the creative potential in new applications- the **challenges** of supporting and facilitating this transition.

The first challenge is **information**: Informing the wider “public” about the abilities of photogrammetry and thus stimulating interest & creating potential user groups.

The second challenge is **training**: the passing of the necessary **knowledge** and the cultivation of the according **skills** to the new users, so that they can successfully on their own or with guidance (even remote) from experts/professionals complete their projects and meet their needs.

The purpose of this study:

This effort aims to act as an introductory handbook, supplying the reader with a basic overview of the fundamental concepts, historical evolution, current capabilities & future prospects of digital close-range photogrammetry. Furthermore, the reader is supplied with basic implementation guidelines, as well as a spectrum of tools available to him/her, as of date.

In this effort to compose introductory material to photogrammetry for a new user, no pre-established notion of the purpose or educational background has been set. Due to this, the structuring of information has been dictated on an assumed common, middle ground, in terms of knowledge background. On a second level though, different user groups should be identified, described and given their own material in order to be optimally introduced to photogrammetry.

68 “Disruptive innovation, a term of art coined by Clayton Christensen, describes a process by which a product or service takes root initially in simple applications at the bottom of a market and then relentlessly moves up market, eventually displacing established competitor.” http://www.claytonchristensen.com”

On Automation & Control

"Following the definition suggested by Gulch, automation is subdivided into:
- **semi-automatic** modules in which a human operator is constantly in control of the process and is being supported by automatic procedures running in real time,
- **automated** modules for which the operator needs to define input parameters prior to running the process, and must carry out quality control at the end of the process, and
- **autonomous** modules which run completely independent of any human intervention."[69]

With this respect, modern day photogrammetric flows are characterized as **automated processes**. Automated software has particular traits as to their use. A common "trap" is feeling at ease in a user-friendly interface, while having little or no understanding of the processes and algorithms beneath. This is effectively:
- a limitation to the quality of the outcome
- a very low chance for successful troubleshooting
- a risk of erroneous outcomes that can go unnoticed.

This is further enhanced by the fact that **self-diagnosis** is missing in most approaches and therefore, each step must be followed by interactive **quality control** in an automated workflow, including editing where necessary.

Quality control and management, as well as the prior **setting of parameters** accordingly, require a certain level of experience. This experience can be created by combining "hours of flight" with a sound theoretical background, so as to amount to critical judgement on behalf of the user.

69 Heipke, C. "Digital Photogrammetric Workstations - A review of the state-of-the-art for topographic applications", University of Hannover

AGENTS OF POPULARIZATION

For anybody wishing to become a full-fledged photogrammeter, the path is relatively clear: a Bachelor degree in Geomatics/Geography, followed by a Master degree in Photogrammetry and Remote Sensing is a straight-forward option. Some of the most important universities offering classes in Photogrammetry can be found on the list below. Nowadays, alternatives include an academic background in Computer Engineering with specialization in Computer Vision.

The matter under examination in this case though refers to **already established professionals in various fields that wish to employ photogrammetry in their “arsenal”**. In this case, another approach is necessary - one that offers a good theoretical understanding so as to avoid the “button-clicker” stereotype, but practical enough to yield successful results in a efficient amount of time and effort.

A good resource that recognizes this challenge is the Geospatial Modelling & Visualization institute (GMV)[70], a **state-funded institution** for the promotion of science and technology. Its purpose is to educate scientists and institutions in order to further their research and discoveries by employing photogrammetric means (alongside other methods). The following list of proposed participants by the Geospatial Modelling & Visualization institute is quite eloquent on their new “user group” orientation:

- Museum, library, and archive staff working in collections documentation and research
- Photographers who wish to move from 2D to 3D content development
- Conservation and preservation professionals dealing with any type of physical material
- People with a passion for rock art
- Archaeologists, anthropologists, classicists, epigraphers, historians, and natural scientists
- Anyone interested in 3D imaging technology and its practical applications
- Virtual reality animators and modellers who want to capture real-world subjects

Their website consists of a substantial number of 3D data acquisition and processing work-flows that are cross-indexed so that the necessary workflow can be identified[71].

In the same spirit lies the 3D Coform project[72] which is specifically targeted to the documentation of tangible cultural heritage, but offers valuable information that can be transferred to other applications.

Another illustrative example for the trending promotion of photogrammetry is Cyark, a **non-profit organization** for the preservation of cultural heritage, that offers a small photogrammetric tutorial as part of its education series, which is intended as school activity for grades as low as 6-12.

Moving away from established foundations, physical space and actual workshops and delving into the realm of **cyberspace**, there is a wealth of knowledge and support in the form of tutorials, tips and project showcases in various levels of expertise and detail. There are various **blogs** that claim to be “aimed at everyone (professionals and non professional) who wish to understand and apply the basic concepts of Photogrammetry[73]” and the list is continuously expanding. Another excellent way of delving into photogrammetry are **forums**[74] related to the photogrammetry and the **communities** of related open source programs, as well as the **hubs** of companies that offer software solution on this field. Lately, Photogrammetry has started to appear in projects in popular **DIY web-places**, such as Instructables[75] and in articles in related **e-zines**, such as Makezine[76].

ISPRS Working Group VI/2 specifically addresses the issue of e-learning and web-based learning. Information about resources and projects can be found on the corresponding site[77] and relative papers.[78]

70 The website has been developed as part of the NSF funded CI-TRAIN project. The CI-TRAIN project is a partnership of institutions of higher education in Arkansas and West Virginia to transform the practice of information technology services for enabling scientific discovery.
71 http://gmv.cast.uark.edu/
72 http://www.3d-coform.eu/
73 https://imagebased3dmodeling.wordpress.com/
74 http://www.virtumake.com/forum/viewforum.php?f=40
http://www.pgrammetry.com/forum/index.php
75 http://www.instructables.com/tag/type-id/category-technology/keyword-photogrammetry/
76 http://makezine.com/2013/08/21/diy-photogrammetry-open-source-alternatives-to-123d-catch/
http://www.tested.com/art/makers/460142-art-photogrammetry-how-take-your-photos/
77 http://misc.gis.tu-berlin.de/typo3-igg/index.php?id=1418
78 Koenig, G. et al, “E-learning – best practice in photogrammetry, remote sensing and gis – status and challenges”, International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XXXIX-B6, 2012, XXII ISPRS Congress

Photogrammetric Training by CHI (Cultural Heritage Imaging)[79]

Online Photogrammetric Software Tutorial (youtube)[80]

> The reader can hopefully find the type of resources most suitable to his educational background and interests by personal research and by help of the following list.

79 http://culturalheritageimaging.org/What_We_Offer/Training/photogram_training/index.html
80 https://www.youtube.com/watch?v=LeU_2SHwhqI

REFERENCE LIST

for a first level of further familiarization

Web-link Database

A very comprehensive link database to websites regarding multiple aspects of photogrammetry has been put together by **Gordon Petrie**[81] and can be accessed here:
http://www.petriefied.info/linksdb.html

List of Helpful Websites and Publications for Close-Range Photogrammetry

http://gmv.cast.uark.edu/photogrammetry/hardware-photogrammetry/canon-5d-mark-ii/canon-5d-checklist/list-of-helpful-websites-and-publications-for-close-range-photogrammetry/

Some very short mentions regarding photogrammetry are listed below:

Associations & Institutions

ISPRS - International Society for Photogrammetry (and the corresponding national-level organizations)
ASPRS - American Society for Photogrammetry and Remote Sensing
CIPA - International Committee for Architectural Photogrammetry
EuroSDR (Spatial Data Research)
GRSS - Geo-science and Remote Sensing Society

Universities

Courses related to photogrammetry are usually offered in the geography/geo-science departments of universities. A background in computer science is also useful, since modern photogrammetry revolves around advanced computer-vision and data handling algorithms. Some important Universities offering classes in Photogrammetry are the following:

- Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University
- Department of Geomatics Engineering, University of Calgary
- Department of Geodesy and Geomatics Engineering, University of New Brunswick
- Nottingham Geospatial Institute, The University of Nottingham
- State Key Laboratory of Information Engineering In Surveying, Mapping & Remote Sensing, Wuhan
- Faculty of Geomatics, Computer Sciences and Mathematics, University of Applied Sciences Stuttgart

Organisations / conferences & corresponding Journals

- ISPRS (International Society for Photogrammetry and Remote Sensing):
  Commission III: Theory and Algorithms
  Commission V: Close range Techniques and Machine Vision
  Publications: International Archives of Photogrammetry and Remote Sensing; ISPRS Journal of Photogrammetry and Remote Sensing
  www.isprs.org

- ASPRS (The American Society for Photogrammetry and Remote Sensing):
  Publication: Photogrammetric Engineering and Remote Sensing
  www.asprs.org

- RSPS (The Remote Sensing and Photogrammetry Society):
  Publication: The Photogrammetric Record
  www.rspsoc.org

- CIPA (Comite International de Photogrammetrie Architecturale):
  Publications and conference proceedings.
  http://cipa.icomos.org/

81 Professor Emeritus at the Department of Geographical & Earth Sciences, University of Glasgow.

- CMCS (Coordinate Metrology Systems Conference)
  Publications and conference proceedings.
  www.cmsc.org

- SPIE (The International Society for Optical Engineering):
  Publications and conference proceedings.
  www.spie.org

Important Publications
- The Manual of Photogrammetry, 4th Ed., American Society of Photogrammetry and Remote Sensing
- Non-Topographic Photogrammetry, 2nd Ed., American Society of Photogrammetry and Remote Sensing
- Introduction to Modern Photogrammetry, E. Mikhail, J. Bethel, J. McGlone, John Wiley & Sons

Companies & Software
- ERDAS - Leica Photogrammetry Suite
- BAE Systems - Socet Set
- Z/I - ImageStation
- PCI Geomatics - Geomatica
- Hexagon Geospatial - Imagine
- Racurs - Photomod
- Trimble - Inpho Suite
- Eos Systems - Photomodeler
- Topcon - ImageMaster
- REALVIZ - ImageModeler (acquired by Autodesk, since 2008)
- PhotoMetrix - iWitness

EDUCATIONAL & SKILL BACKGROUND

for a thorough understanding of photogrammetry

Theoretical background

Photogrammetry has its own body of theoretical knowledge, but it also draws important elements from a great variety of disparate fields of knowledge. It is said that in order to really understand a topic, one needs to understand a bit of the level of complexity just below it. This handbook is intended for potential/new users -therefore at a primary level- but aims nonetheless to offer the necessary tools for faster familiarity and deeper understanding of photogrammetry.

For this reason, the following list of scientific fields that were deemed as an important contribution to the understanding photogrammetry was compiled. The main photogrammetric theory will be presented mingled with these interconnecting disciplines.

Wishing to avoid the traditional layout of an encyclopedic account, emphasis was given on the particular aspects of each discipline that are most related to photogrammetry.

Some of these issues, such as light or the human eye, might on first account seem common knowledge, but it is preferable to address them, since our confidence on common, everyday topics sometimes is born out of simple familiarity rather than a clear and fundamental understanding.

1. Evolution of thought on light & vision
A trip in time so as to appreciate the slow build-up of necessary knowledge for photogrammetry
2. On the Nature of Light
Basic understanding of the nature of light and therefore sight
3. Geometrical Foundations
For understanding the travel of light in space and the interaction with matter in Geometric Optics
4. The “discovery” of Central Projection & Perspective
The basis for photograpic image formation
5. Human Eye as an Optical Instrument
Understanding how the eye works is essential to understanding the parallels with the photographic camera
6. Binocular Vision & Parallax
Understanding how binocular vision works is essential to understanding how depth estimation works
7. On Lenses
For understanding the impact of lenses on image formation
8. The Photographic camera: the Mechanical Eye
Mastering the first most important instrument in a photogrammetric work-flow
9. Digital Photography
The transition to digitalization and the new capabilities of digital photography
10. Photogrammetry
Lay-man terms for the new photogrammeter
11. Digital Photogrammetry & Computer Vision
Overview of the basic algorithmic processes in Digital Photogrammetry
12. Digital 3d Graphics
Understanding basic aspects of digital 3d geometrical information

The above list presents a logical “flow” of stackable knowledge. For the purpose of the handbook, though, these fields of knowledge have been divided in two parts, in the following theoretical section and in the appendix section in the end of the handbook, based on their “share” and priority in the understanding of photogrammetry. The foundations for photogrammetry can be found in the following section, but the intrigued reader will surely benefit by reading the further extents of knowledge presented in the appendixes.

Practical skills

All the above subjects offer valuable support to the potential photogrammeter but constitute a more or less “academic” background, in the sense that they don’t necessarily grant the user direct skills or know-how for the practical application and execution of a photogrammetric project. In these terms, a potential photogrammeter is advised to gain experience and cultivate the following skills:

- good use of a digital SLR in full manual mode with deep understanding of proper exposure and focus, as well as colour correction/white balance
- basic skills in digital image processing and archiving
- ease with general computer skills to learn and experiment with new software
- experience in handling 3d geometry

SECTION B)
IN THEORY

<abstract:>

Before attempting to execute a photogrammetric project, a theoretical session, aimed to cultivate a knowledge background, is advised. In this way, one can benefit from the automations of digital photogrammetry without the risk of blind "button-clicking".
The presentation is structured in a "stackable" way with each chapter facilitating the understanding of the next, therefore "serial" reading is advised.
All the following was written with a vague reader profile in mind- depending on academic background, each person might have different levels of familiarity with the following topics.

CONTENTS

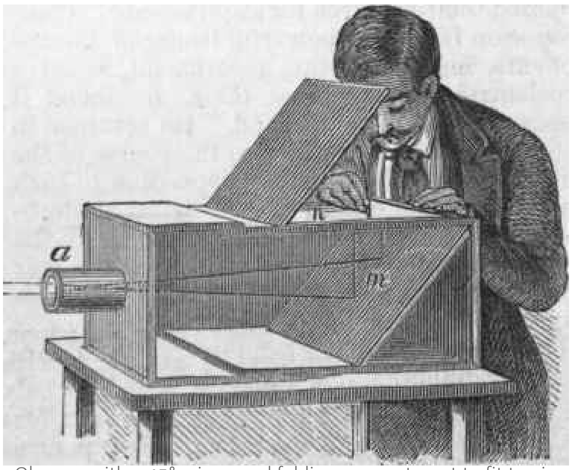
PHOTOGRAPHY

Understanding the mechanics of photography is essential to photogrammetry. The photographic camera can be treated as a mechanical analogue of the (human) eye, but the importance of the technological achievement of photographic capture is immense: the ability to store, share and analyse the visual information about space (and time) makes photogrammetry possible. For this reason, we will analyse photography from its origin, thus making somewhat of a historical review of its evolution.

I. The Pinhole Camera

camera obscura + portability = pinhole camera

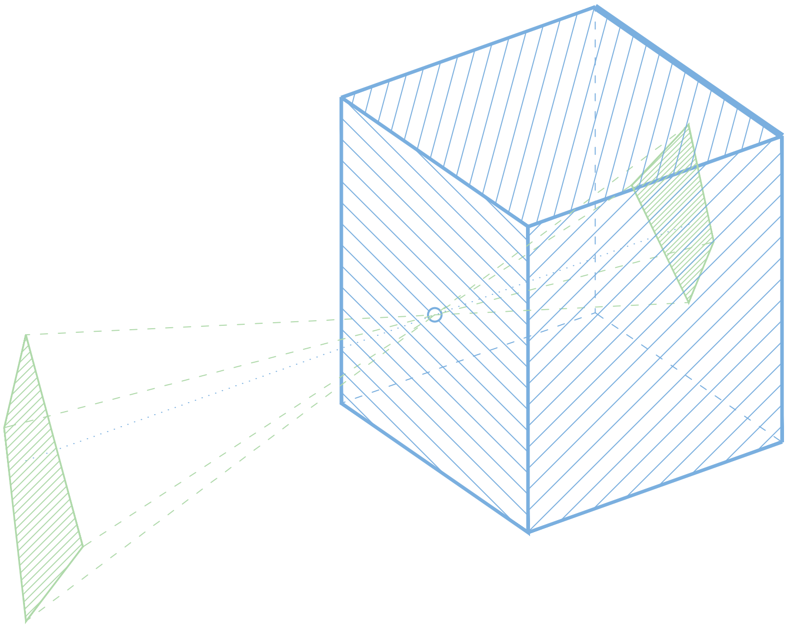
The best way to explain the way the modern day photo-camera works is to examine its simplified precursor, the **pinhole camera**, also known as "**camera obscura**"[1].



Camera Obscura with a 45° mirror and folding compartment to fit tracing paper[2]

The pinhole camera is a simple **optical device**. Most commonly, it consists of a solid, light-proof, hollow box (whose interior is therefore in utter darkness) with a small opening[3] on one of its sides. When the side with the opening is exposed to light, the light rays passing through the tiny pinhole meet the interior surface opposite to the opening and create an inverse image of their source, according to the principles of central projection. Thus, an upside-down and scaled-down version of the surroundings facing the box is depicted. The resulting image can either be viewed directly by the subject with the help of another opening, or mirrors or a translucent screen (with an appropriate setting, so that no more light-rays "invade" the camera). At first, the image formed was flitting- the camera was used for tracing images on paper by hand. Later on, it would be made possible to capture the image by means of a flat panel with a light-sensitive coating, thus creating a photograph[4].

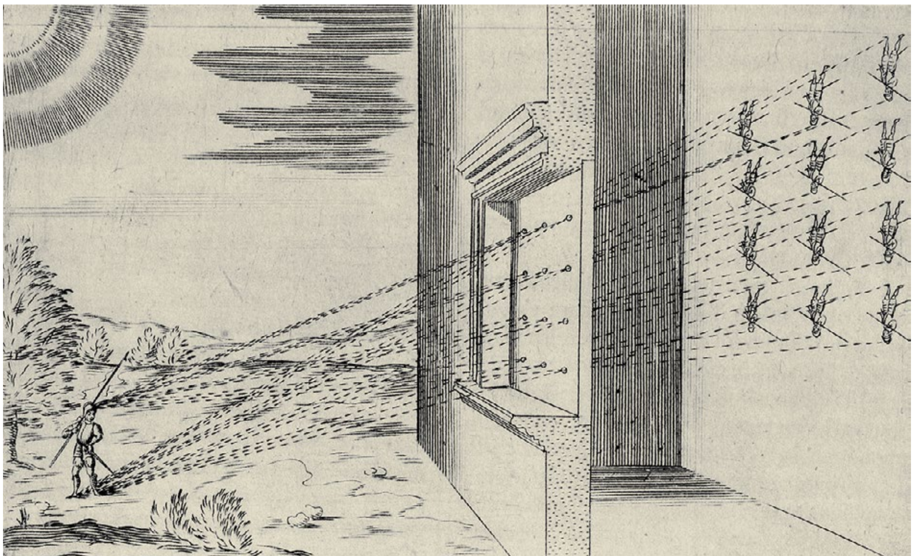
1 Latin, for "dark chamber".
2 http://chestofbooks.com/reference/American-Cyclopaedia-2/Camera-Obscura.html
3 The size of the hole can be accurately defined. The optimum diameter is the one that is small enough so that the bundle of light rays is the smallest thinnest possible (sharper focus) but big enough so that light rays passing through do not react as waves and suffer diffraction. More on the formula on the work Nature (1981) by Lord Rayleigh (J.W.Strutt).
4 For accurate calculation of exposure time for each pinhole camera design (f-stop), please see: http://www.pinhole.cz/en/pinholedesigner/



` Schematic Sketch of a pinhole camera[1]

The observation of the **phenomenon behind this invention** (inverse creation of image of objects) is noted from early antiquity[2], due to the frequency of its natural occurrence. The pinhole camera has been used variously and frequently in conjunction with pictorial arts. It rose to high interest in the years of the Renaissance[3] for the **study of the laws of central projection,** for the education of the painters in the accurate, perspective depiction of space[4]. Other artists, such as Vermeer[5], have been known to use their canvas as a projection surface in order to trace the projected images- an example of an early use of a rotoscope[6].

The first implementations were in the shape of a closed room with a small opening to let the natural light in- the wall facing the opening serving as a projection screen for the depiction of the landscape outside (giving rise to the name "camera"). Later on, around the 17th century, it was reshaped to a portable device[7].



Camera Obscura - Mario Bettini 1642

1 http://www.northlight-images.co.uk/article_pages/Canon_1ds_pinhole.html

2 As early as 5th century BC in China. Notable thinkers commenting on the phenomenon include Aristotle, Ibn Al-Haytham, Roger Bacon, Gemma Frisius and more.

3 A detailed presentation by Leonardo DaVinci can be found in Codex atlanticus (c. 1485).

4 On 1558 we have detailed descriptions by the Renaissance painter Giovanni Batista de la Porta about the construction of a camera obscura chamber and its use in pictorial arts.

5 For more information, visit: http://www.essentialvermeer.com/camera_obscura/co_one.html#.Visdoyv0Org & Philip Steadman's «Vermeer's Camera: Uncovering the Truth Behind the Masterpieces», 2002, Oxford Press

6 For more information on the rotoscope, see Max Fleischer's innovative work "Out of the Inkwell", 1915.

7 The box form of Camera Obscura shown at the right was invented by Johann Zahn in 1685.

CENTRAL PROJECTION & PERSPECTIVE

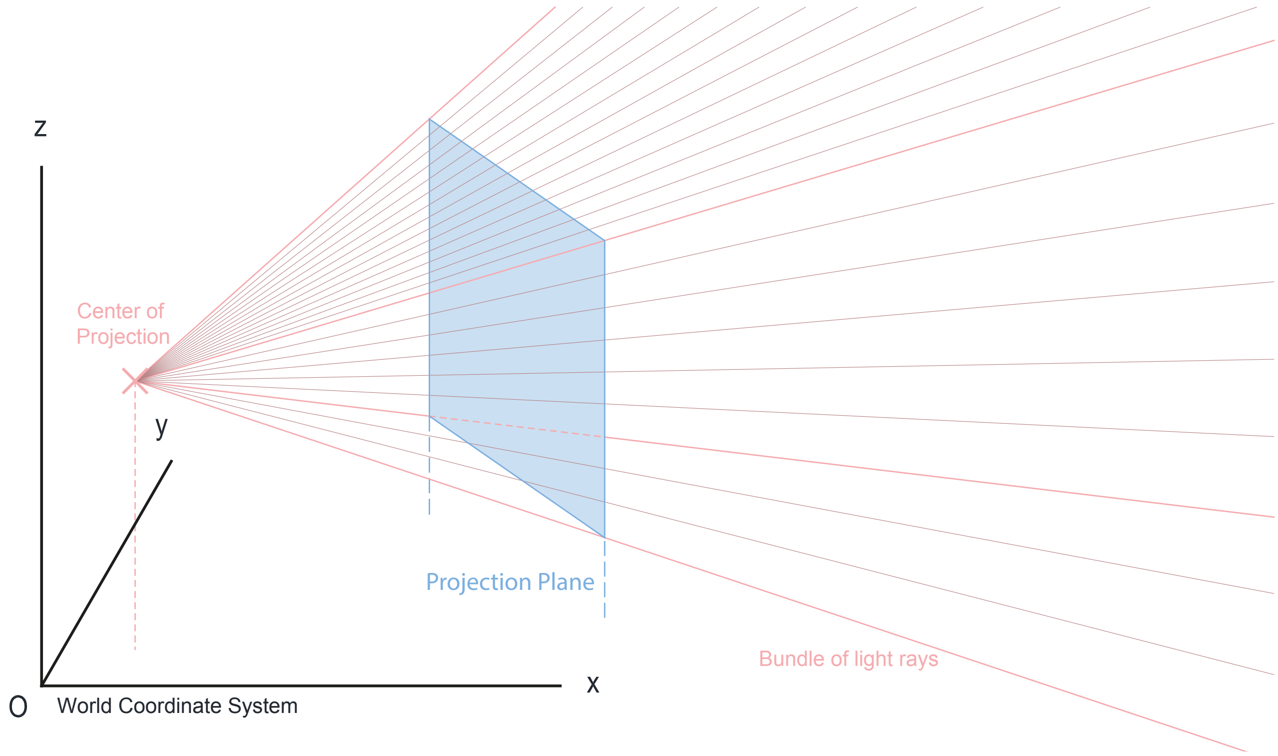
keywords: < Projection Point, Projection Plane, 3dimensional Object, Central projection, Perspective Projection >

Already in the model of the pinhole camera, there is an important understanding for photogrammetry: the fact that the image thus created can be approximately described as a product of a projective transformation method, namely of central projection. Therefore, understanding Central Projection gives an understanding of the rules behind the creation of an image through the photographic procedure.

Central Projection - in summary:

Central projection is a method of projective transformation. In essence, it’s a mapping process of a set of elements into another subset. In this case, there is the **mapping of points from 3d space on a 2dimensional surface, based on a given set of rules**. The premise for this mapping is the **rectilinear connection** of points in Euclidean space with a specific point of interest, termed the **projection centre**. Each connecting line represents a **light-ray**. The next important component is the definition of a plane in space, termed as **projection plane**. The projection plane intersects a **bundle** of these connecting light-rays. The point of intersection between a light-ray and the plane forms the **projection image** of the corresponding point.
By applying this intersection for all points, a 2dimentional image of 3d space based on the rules of Central Projection is formed. The central projection space has its unique attributes when compared to Euclidean geometrical space, mainly the **convergence of all parallel lines to a point “at infinity”**. Lines parallel to the projection plane remain depicted as parallel and all other spatial directions appear to converge at a point, termed as “**vanishing point**” for each direction. The reason why it is of such interest and importance since antiquity is because it describes with relative success the way humans view the world, namely, the way that images are formed and perceived by the human eye[1].

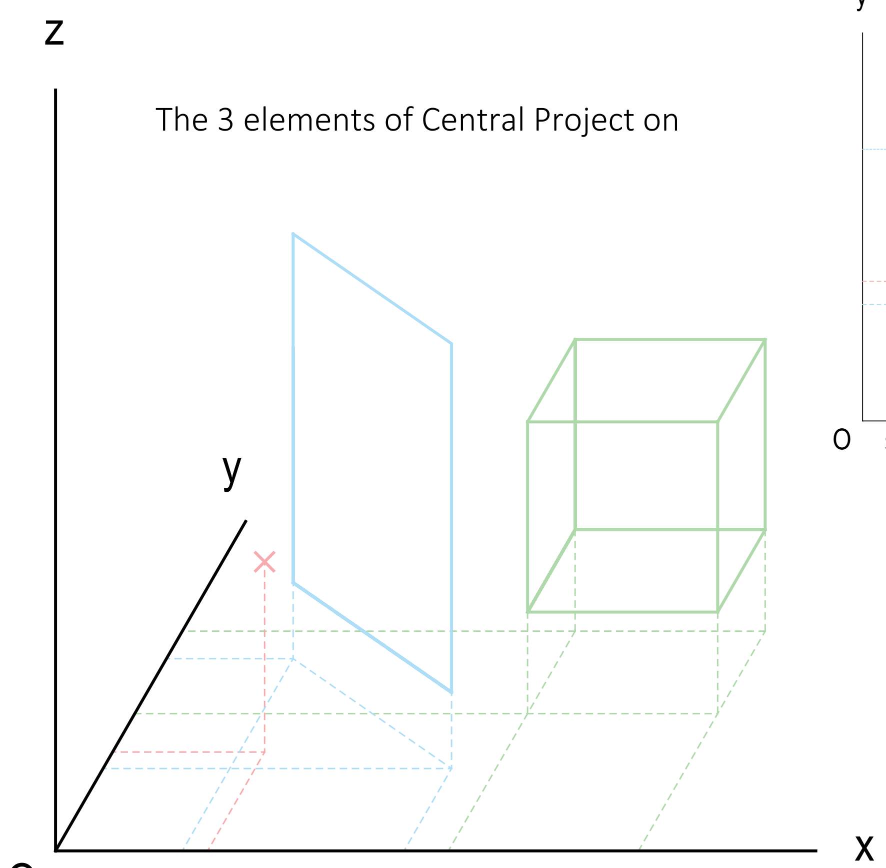
“Field of view” of a Central Projection



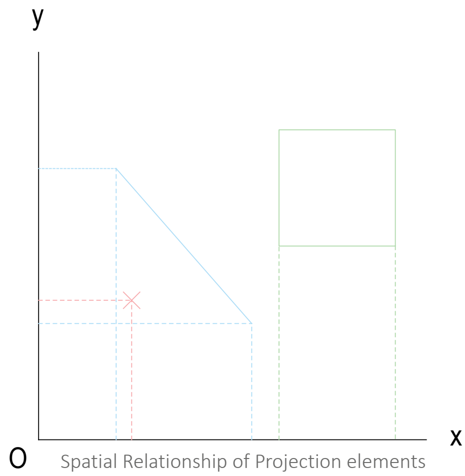
The spatial relationship between Centre of Projection and Projection Plane defines the “field of view” of the projection, i.e. the size and orientation of the light-ray bundle.

1 For more on this, see Appendix.

Step by step construction of a central projection

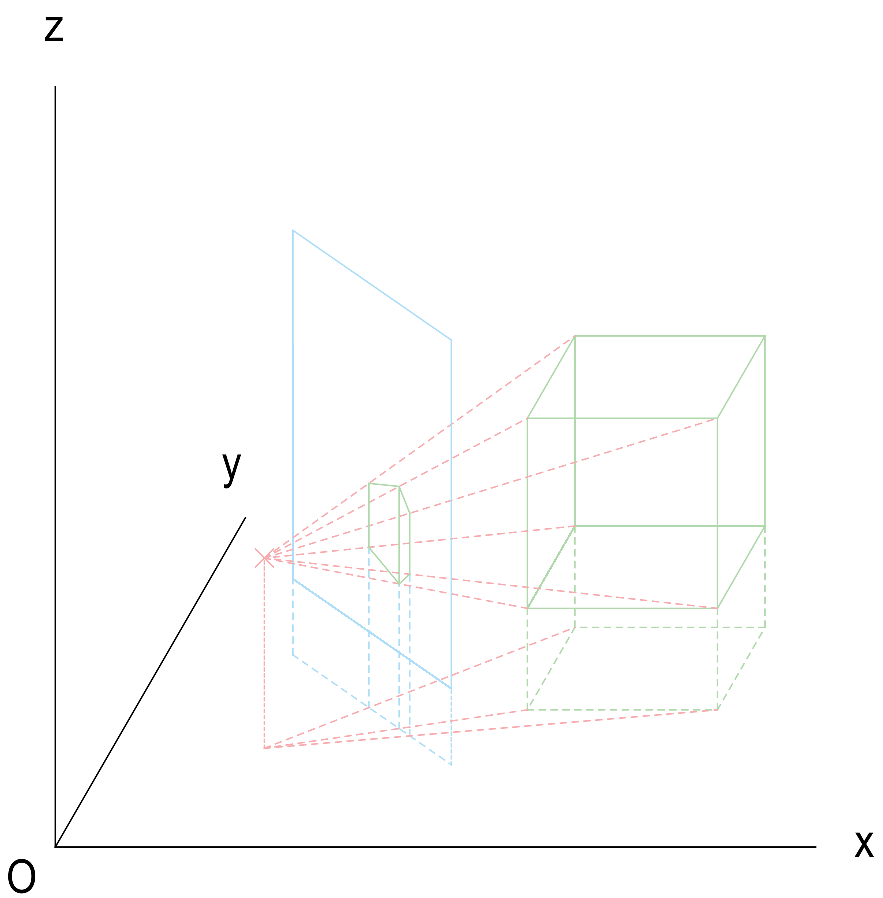


O World Coordinate System

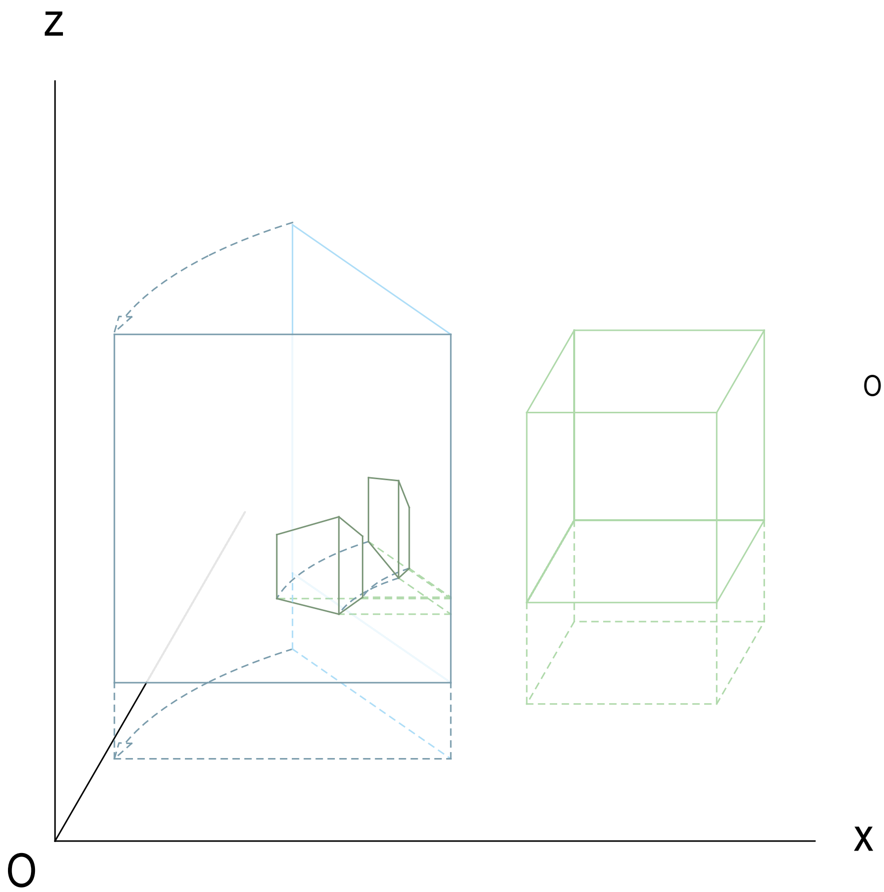


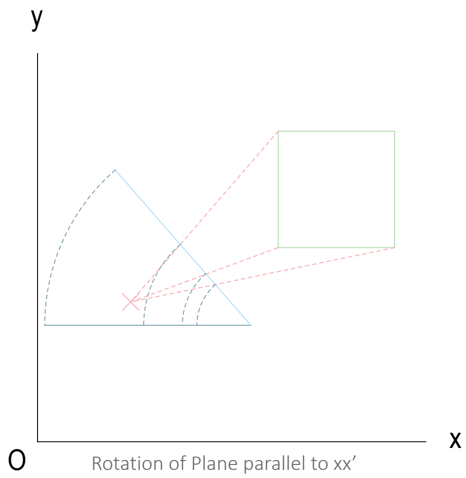
Spatial Relationship of Projection elements on XY plane

The XYZ-axes denote 3d space. The axonometry employed is “axonometrie Cavalière” with the unit vector of the y axis a fraction (namely ½) of the unit vectors of x and z axes. The reason for this is to better simulate visual perception. The red X point denotes the projection centre, the blue plane is the projection plane, while the green cube represents the 3d material object of interest.



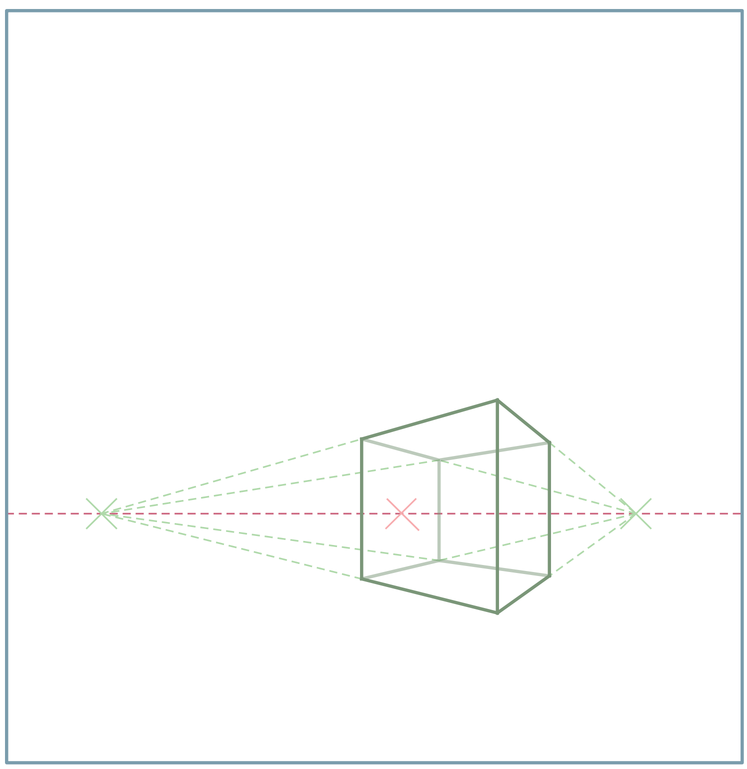
Connection of vertices of object with Centre of projection. Intersection with Projective Plane and Formation of perspective image

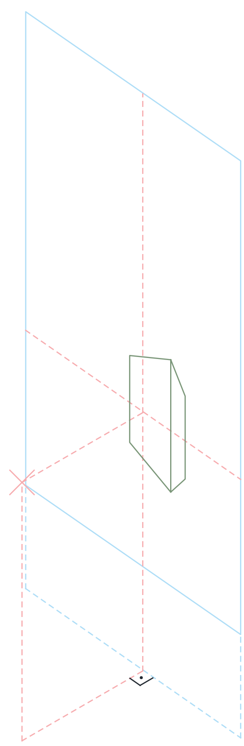




Rotation of Plane parallel to xx’

Rotation of Projective Plane to render it parallel to xz plane, purely for viewing purposes

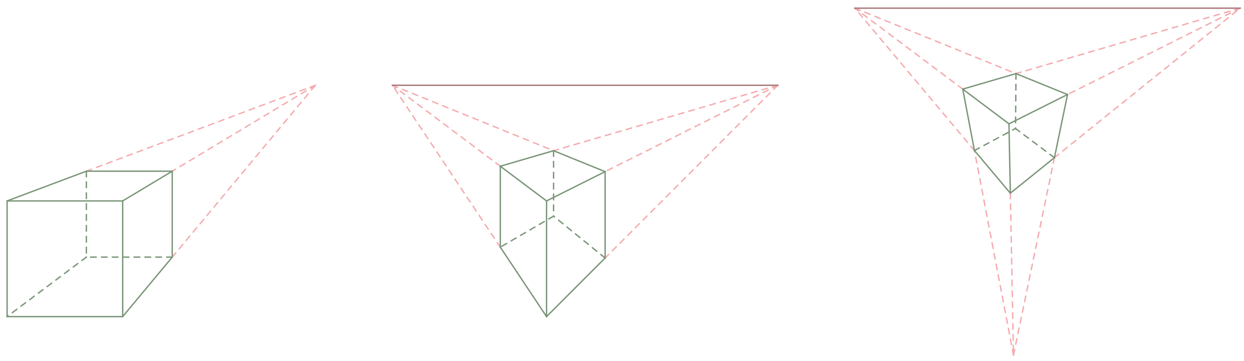




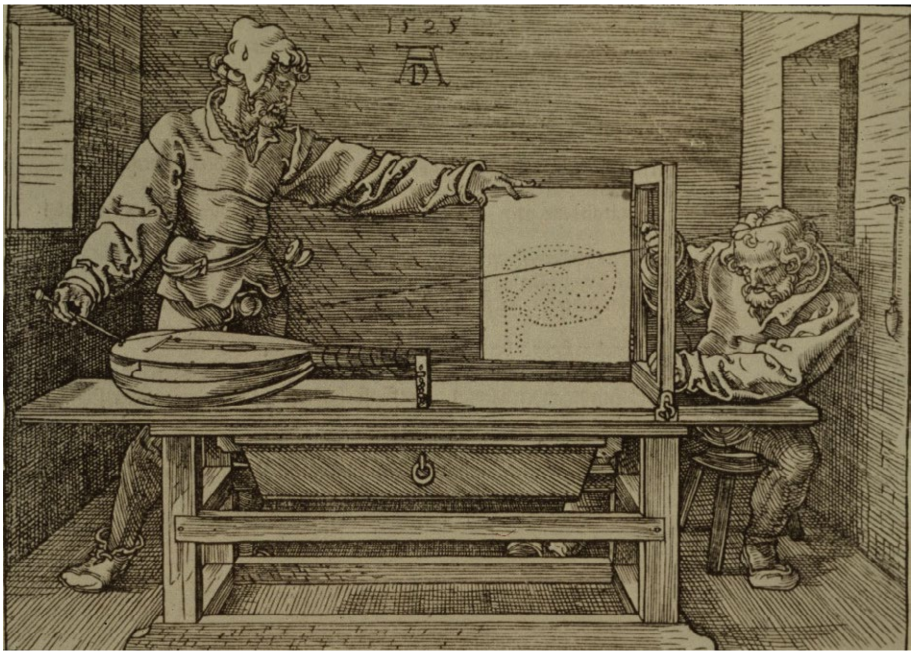
Construction of “Vanishing Points” & “Horizon” line.
The Horizon line is defined by the Z coordinate of the Projection Centre.
With the help of vanishing points the edges of the object that are hidden from view can also be drawn.

The projection centre is the only point that whose projection image is not defined: it is projected vertically on the image plane.

Vanishing Points



Perspective Projections of a cube: Depending on the relative location of the cube's edges and the image plane, it can be imaged with a single, 2 or 3-vanishing points.



Albrecht Dürer "Man Drawing a Lute" (1525)[1]

Evidence of a clear understanding of this process can be found on the works of important artist and entrepreneur in graphical/pictorial arts, Albrecht Dürer (1471-1528), who had invented a device to supplement the accurate perspective drawing of scenes, effectively creating a "human analogy" to a camera.

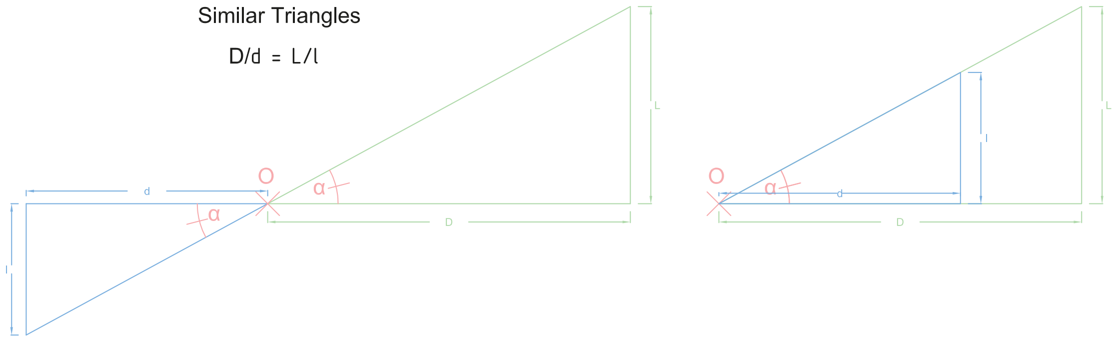
1 https://upload.wikimedia.org/wikipedia/commons/1/1a/D%C3%BCrer_-_Man_Drawing_a_Lute.jpg

Important Foundations for Photogrammetry, derived from Central Projection:

The notion of Scale

Each depicted "image-object" is a scaled version of the real, physical "world-object". The scale can be larger or smaller, depending on the **spatial relationship** of the 3 projection elements: **object, projection centre & projection image plane**.

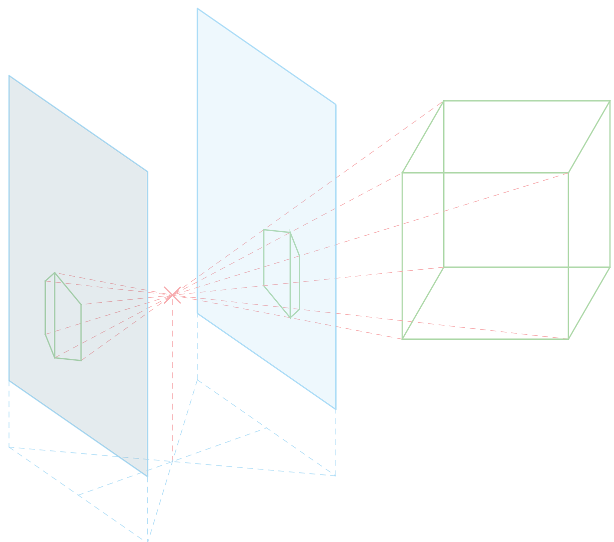
The rules to define the size-ratio between an object and its image are given by the **Intercept Theorem**, also known **Thales' Theorem**, i.e. about the ratio of lengths in **similar triangles**[1].



Notes:
1) In this explanatory sketch, for better clarity, a simple length is used as opposed to a complicated object.
2) Right-angled triangles are presented, which is a subcategory of the general case. The projection of the centre of projection and the image plane is perpendicular, therefore, only one more angle is necessary for the two triangles to be regarded as similar.
3) The left and right sketches are equivalent.

** The "Mirroring[2]" of the Projection Plane*

Based on the above, it follows that the depicted image will be the same, whether a projection plane is located in front or behind the centre of projection point, as long as the two planes are parallel and their distance to the projection centre remains the same. Therefore, these two formations are **equivalent**. The location of the image plane behind the sensor is the "norm" when sketches refer to the **photographic capture** of perspective images.

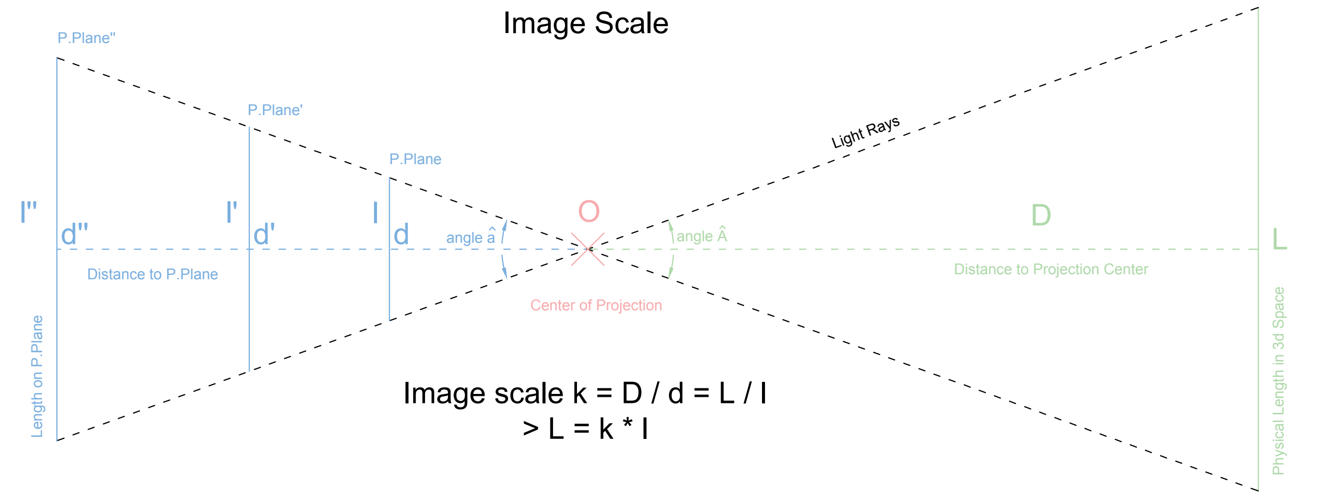


Note: The image on the plane behind the centre of projection is seen "from the back", as if the plane was transparent.

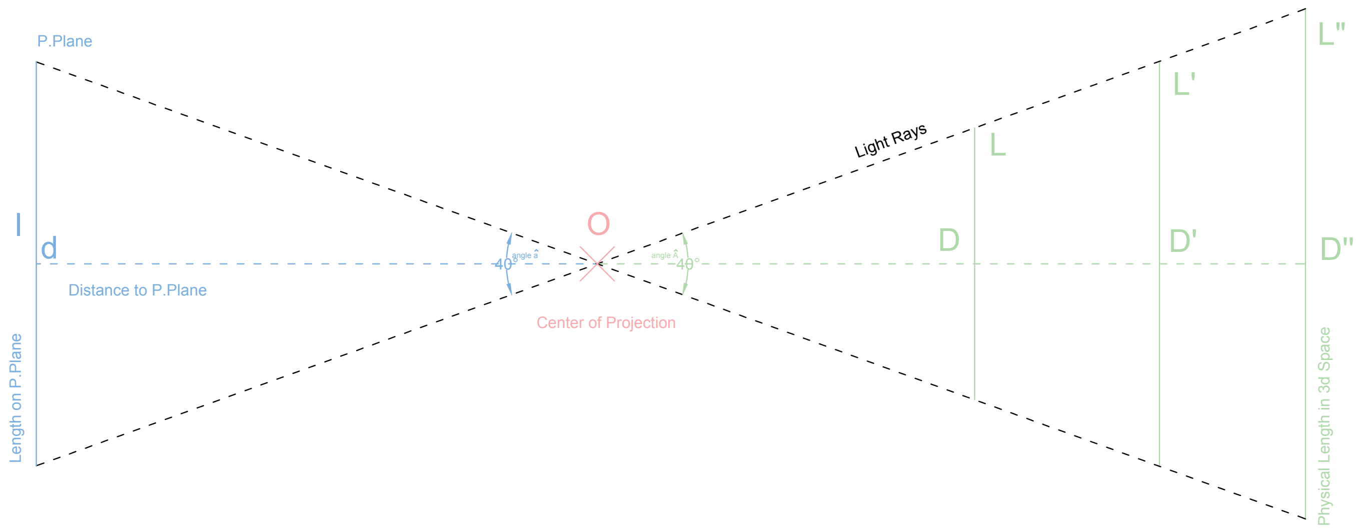
1 In geometry two triangles are similar if and only if corresponding angles have the same measure. This can happen if they have two congruent angles, or if all the corresponding sides have lengths in the same ratio or if two sides have lengths in the same ratio and the angles included between these sides have the same measure.
2 Their correct relationship is that of an isometric transformation of a "half-turn".

Image Scale

By applying the Intercept Theorem on the similar triangles, there is a clear calculation of the **image scale k**:



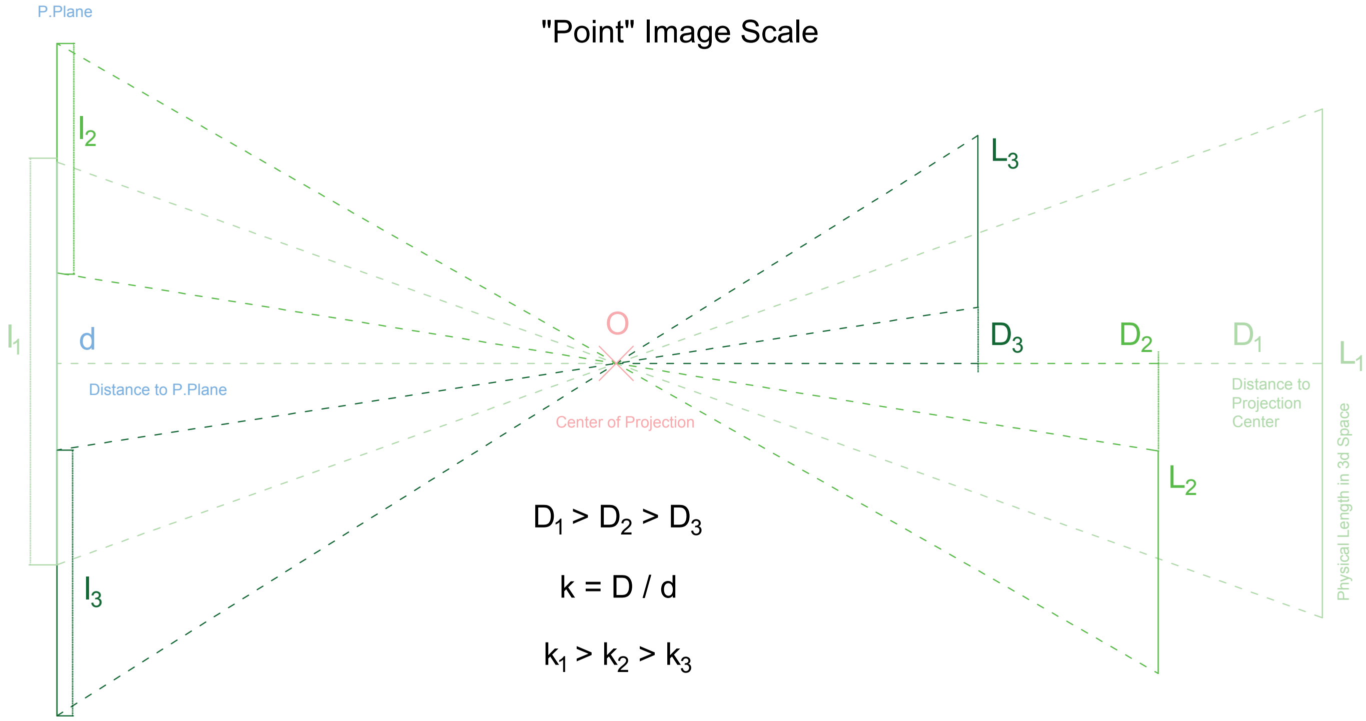
Depending on the distance of the Projection plane, the same physical length is depicted in various scales. Thus, the **foreshortening effect of perspective depiction** is explained.



It follows, that the opposite is also true: different physical lengths in various distances can have the same projection.

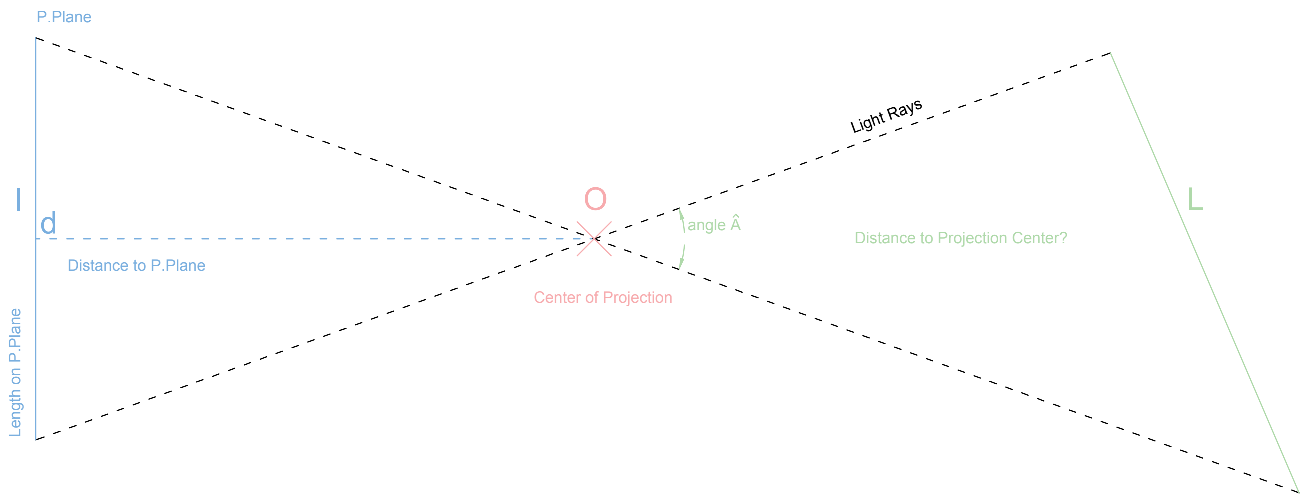
"Point" Scale

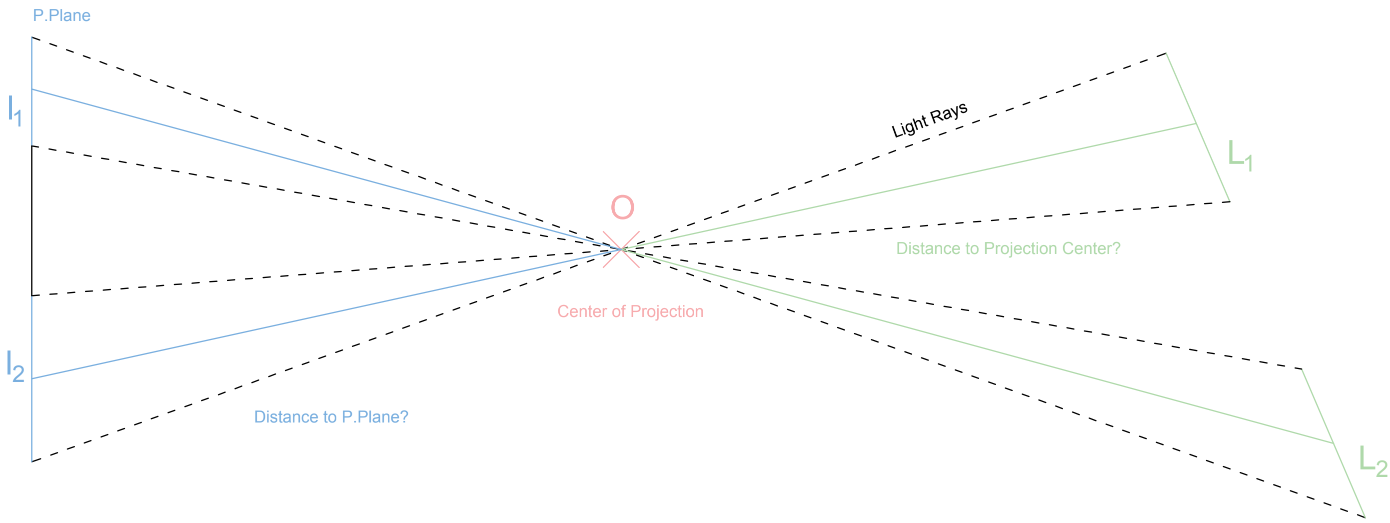
Of course, in real world situations, not all depicted points in space are located at the same distance from the centre of projection. This means that each point or set of points(lengths) is depicted at **its own scale**. This means that an image does not contain objects at a single, uniform scale, but it can nonetheless be characterised by a **"mean" value of scale**, as long as the objects depicted are relatively not too far apart from each other in the real world.



"Variable" Scale

Also, in real world situations, not all physical lengths are parallel to the projection plane. This means that similar triangles are no longer formed. Straight lines at **directions not parallel to the projection plane** have variable point scale.

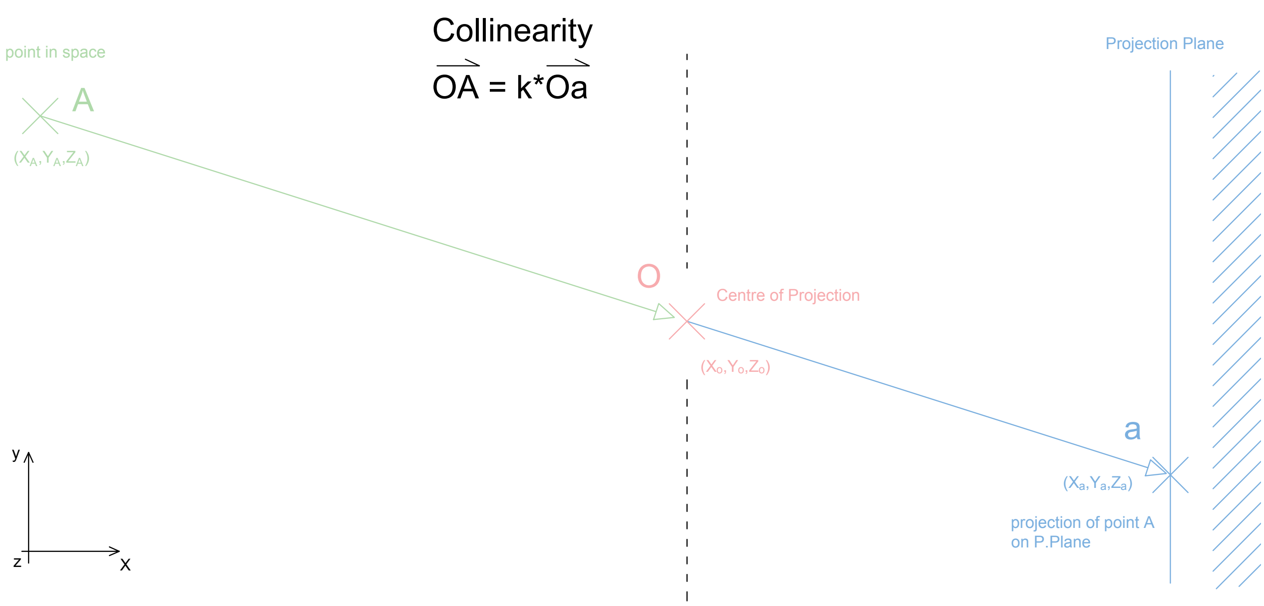




This "uncertainty" becomes even greater when objects are pictured at the further edges of the canvas.

Collinearity

Another important understanding for photogrammetry is the fact that the image point and the real point are connected by a rectilinear ray that passes from the centre of projection, as dictated by the central projection model. This, in other words, means that the **vectors** connecting the image point with the centre of projection and the centre of projection with the real point are **collinear**.



Summary

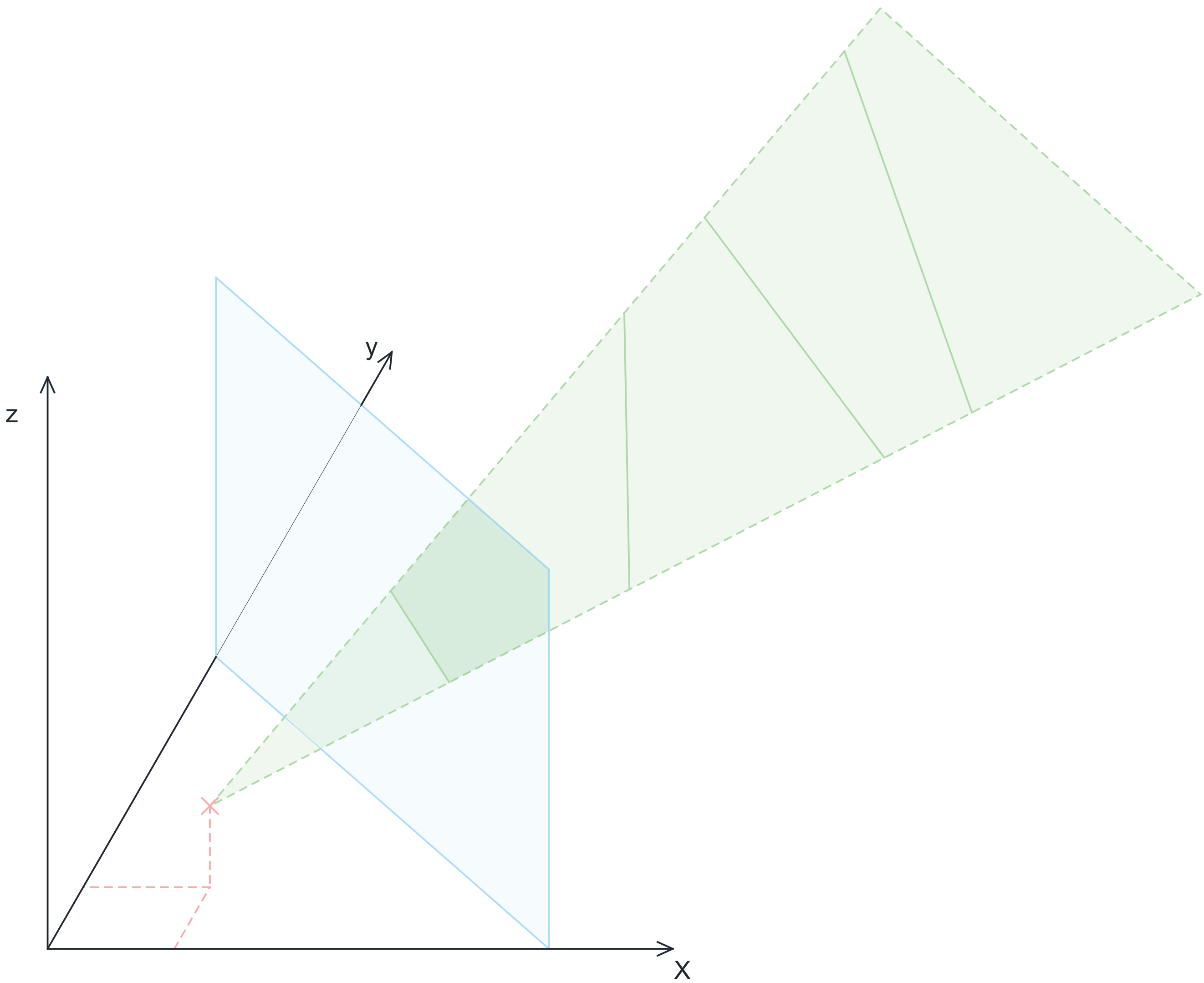
By now, it is clear that the **depiction of an object in central projection and its physical dimensions are “bound” together by simple geometrical relationships**. This fact allows the potential to calculate the physical dimensions of an object given its depiction and vice versa, if enough information is provided.

This understanding is fundamental to photogrammetry.

The relationship of the depiction to the physical object, though, is not straight forward. Given a **perspective image** and the **location of the centre of projection with reference to it**, the **bundle of light-rays** that formed the image can already be reconstructed.

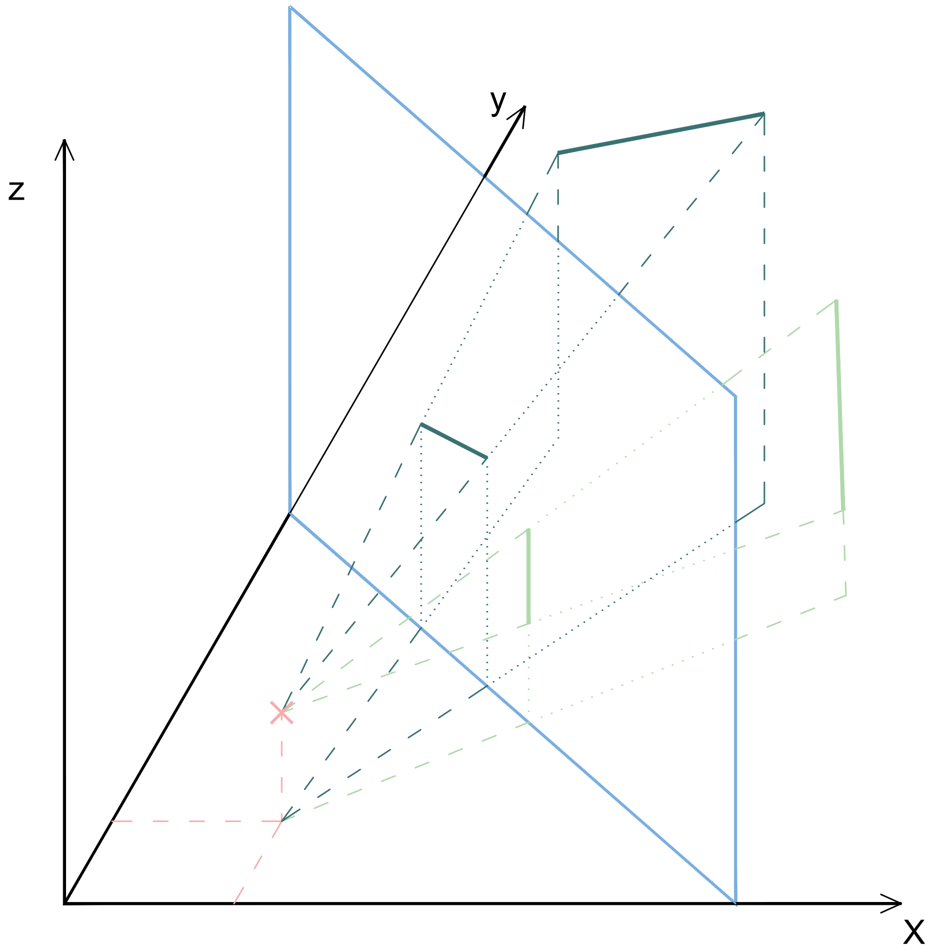
When drafting the image, the light-rays were treated as if originating from 3d points in space and ending on the image plane - now they are **traced backwards**[1]. Their new origin is known -the centre of projection- and a point on their path too -each image point. Therefore, their **direction in space** is defined. But if we want to trace each light-ray back to its original starting point -the 3d point- there is yet not enough information. Therefore, we cannot yet estimate the exact shape or size of the physical object.

The following sketches illustrate the ambiguity:

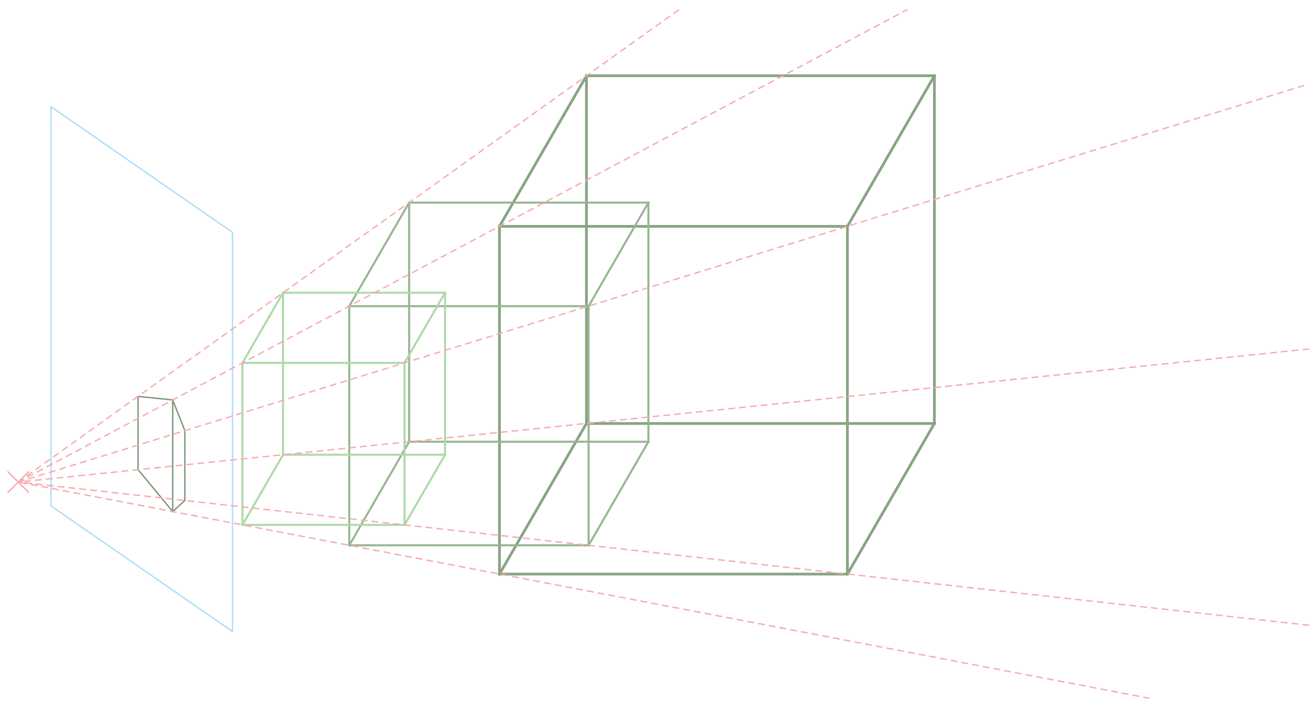


Without any other information, the depiction of this length could belong to any of the above 3d lines.

1 The geometry of classical optics is equivalent no matter which direction light is considered to be moving in, since light is modelled by its path, not as a moving object.



For lengths on a plane parallel to the projection plane, the distance from the centre of projection is adequate information to derive the physical length. The opposite is also true: given the physical length of a depiction, its distance from the centre of projection can be calculated. For lengths on all other planes, the 3d coordinates of their start and end vertices are necessary.



The depiction on the image plane could belong to any of the above cubes. More precisely put, it could belong to any shape other than a cube, but human vision tends to interpret shapes based on known patterns: this is exactly the foundation for optical illusions. Given the distance of the cube's parallel edges to the centre of projection, the cube can be reconstructed.

Closing

The task of 3d point restitution belongs to the science of photogrammetry.

Different methods for this can be employed, which will be presented in later chapters.

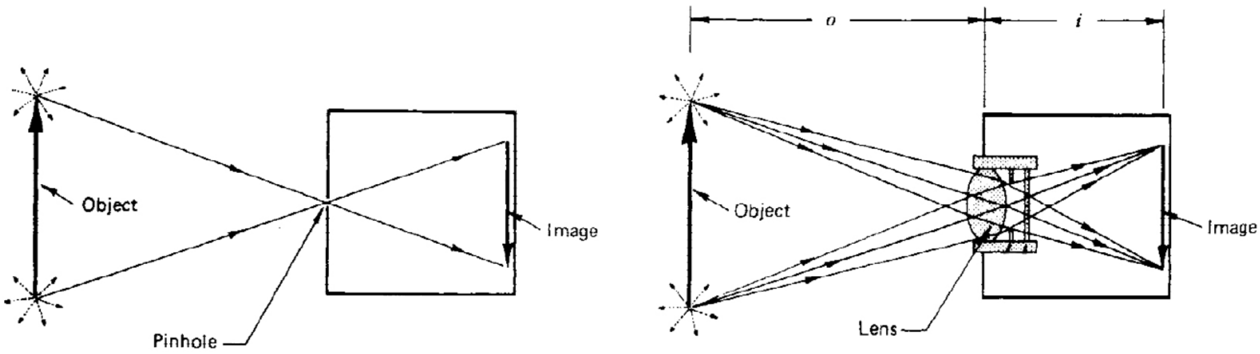
In **photogrammetric terms**, the projection plane is termed as **image (sensor) plane,** the projection of the centre of projection on the projection plane is termed as “**principal point**” and its distance from the image plane is represented by the **principal distance c**.

From now on, the photogrammetric terms will be used instead of the geometrical ones.

II. The Simple Lens Camera

pinhole camera + lens = simple lens camera

Lenses are one of the most important elements of the photo camera, since they define to a large extent the image formation mechanism.



Explanatory Schemas of pinhole camera with comparison to simple lens camera[1]

Further developing the model of the pinhole camera, the goal was to maximize the incoming light rays, without enlarging the pinhole. This is where the implementation of the convex lens proved formative. Therefore, the next evolution step was for the opening to be fitted with a convex lens[2] for sharper focus of the light rays[3], creating a device, which for purpose of this presentation will be termed as **simple lens camera**[4].

The central projection model still applies for the formation of the image, but the centre of projection, instead of a point is space, is now identified with the lens system, which brings about its intrinsic complications.

In order to understand the details involved, the **general properties of lenses** will be presented first and following, **their properties as camera lenses**, when employed on the camera device.

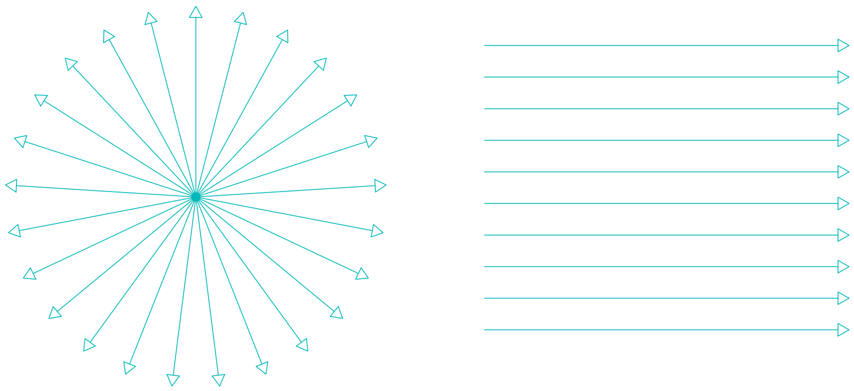
1 Lillesand, T. et al, (2015) “Remote Sensing and Image Interpretation, 7th ed.”, Wiley
2 The replacement of the pinhole with a converging lenwas first described by the Venetian, Daniel Barbaro, in 1568. http://physics.kenyon.edu/EarlyApparatus/Optics/Camera_Obscura/Camera_Obscura.html
3 On 1550 Girolamo Gardano succeeds in a more focused and strong picture by inserting a convex lens on the pinhole.
4 The difference between a simple photo camera fitted with a lens and a pinhole camera, as we will see in the following, is the absence of radial distortions due to the curvature of the lens, as well as infinite depth of field as a result of the absence of a focal length.

ON LENSES

Lenses interact with light-rays in specific and useful ways and as a result, lenses are incorporated in light-sensitive sensors, whether the case is the human eye or the photographic camera. In any scenario, they have some basic properties that are presented here for later use.

Lenses can bend and **guide** the travelling direction of **light-rays** in space, based on their surface/shape.

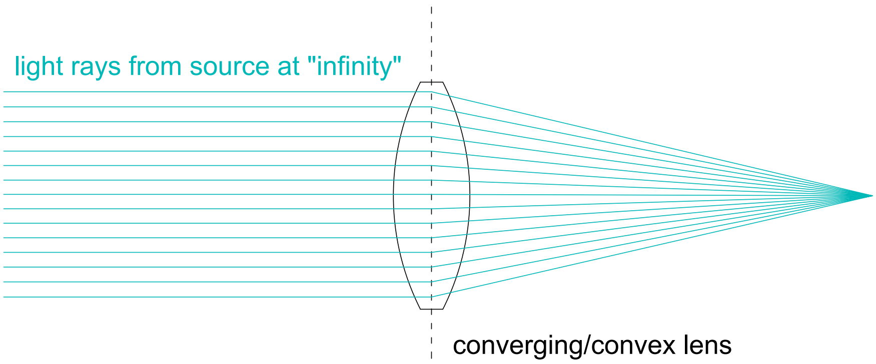
** It should be noted that light rays originating from a source regarded at “infinite” distance are modeled as traveling space in parallel. Light rays originating from nearby point sources are radiated divergently in all (allowed) directions in space.*
> For more information on this, see appendix “On the Nature of Light”.



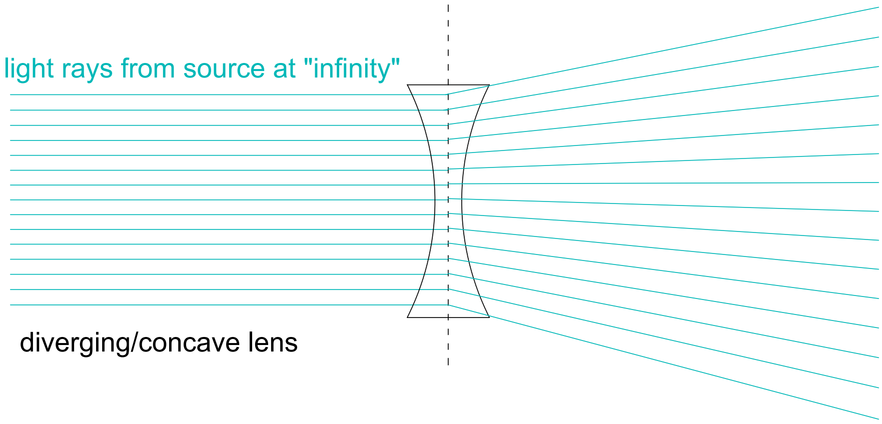
Light Rays originated from point source (left) and Light Rays traveling from infinite distance (right)

Types of lenses

The most interesting type of lens for the scope of photography (& therefore photogrammetry) is the **convex** lens type that can converge/focus light rays on a single point.



Convex lenses can “gather”/converge light rays



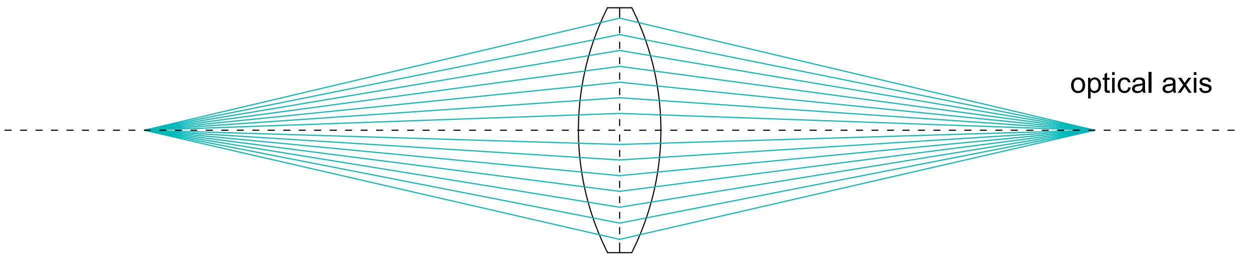
Concave lenses spread the light-rays

Lens Properties

All lenses are characterised by the following properties that are of interest to photography:

- *Optical axis*

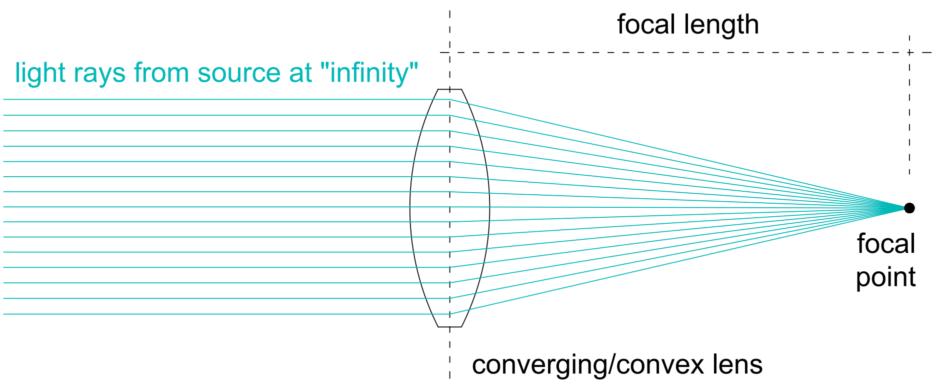
The optical axis is the imaginary axis of **rotational symmetry** of any optical system. It passes through the centre of the curvature of the lens(es).

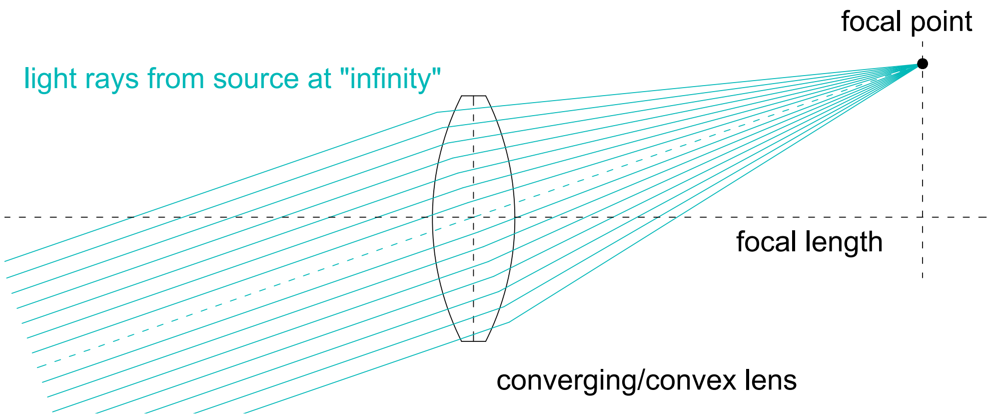


Optical Axis and paraxial rays

- *Focal Length*

The focal length of an optical system is the distance over which parallel rays are brought to a focus. It is a **constant** that **describes the system** and measures how strongly the system can converge or diverge light. A system with a shorter focal length has greater optical power than one with a long focal length- that is, it bends the rays more sharply, bringing them to a focus in a shorter distance.





f the distance at which parallel light rays (distance of light source / infinity) are focused (intersect) to a point[1]

The formula that governs the relationship between the distance of a source point and its image with the focal length of a lens is as follows:

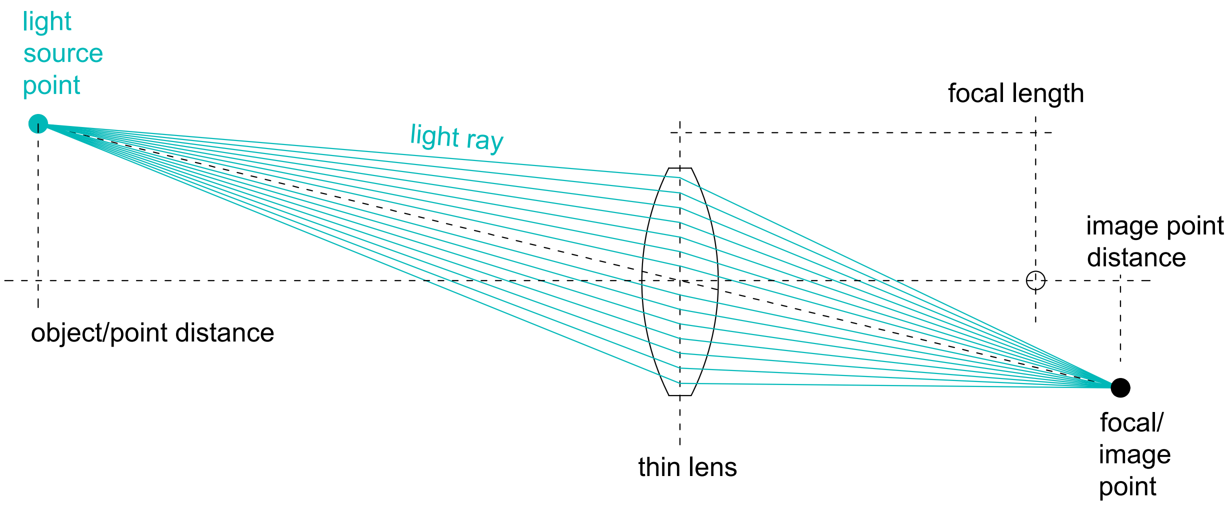
$$1/s_o + 1/s_i = 1/f$$

If s_o is regarded as ∞ (infinite), then $1/s_o = 0$, it follows that $1/s_i = 1/f$ and $s_i = f$.

This explains why parallel light-rays are focused at focal length.

For any other $s_o < \infty$, it follows that $1/s_o > 0$, therefore $1/f - 1/s_o < 1/f$ and $1/s_i = 1/f - 1/s_o < 1/f$. Therefore, $s_i > f$.

This dictates that all light-rays coming from sources nearer than "infinity" are focused farther away than the focal length.

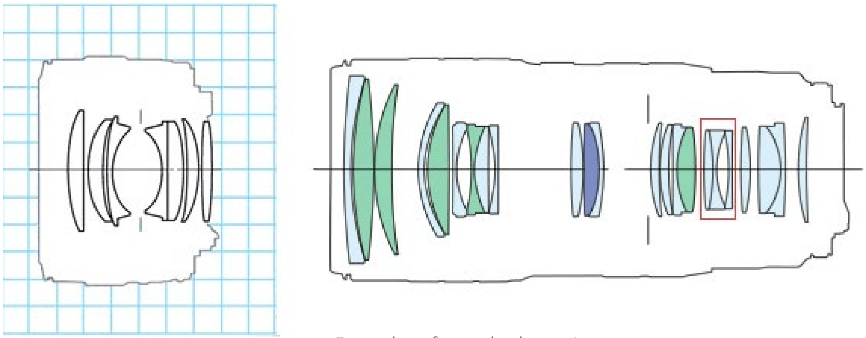


** The focal length of a lens is directly related to its shape, namely its curvature : $1/f = (n-1)*(1/R_1 + 1/R_2)$, where n is the refractive index of the lens.*

Single and Complex Lenses

At the beginning, a single, carefully hand-manufactured lens was used. Soon thereafter and by rule nowadays, cameras contain "**complex lenses**", which actually are systems comprised of various «simple lens elements». More complicated systems with multiple elements (2-20 elements) tend to yield better image formation results, since the variously shaped elements coordinate to balance each others "flaws", as will be explained later.

1 http://www.met.reading.ac.uk/pplato2/h-flap/phys6_3.html



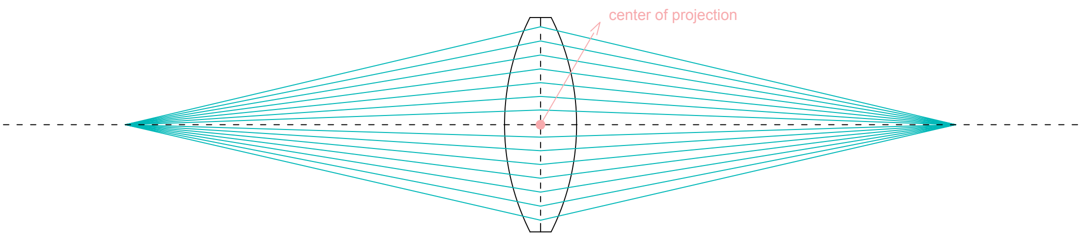
Examples of complex lenses[1]

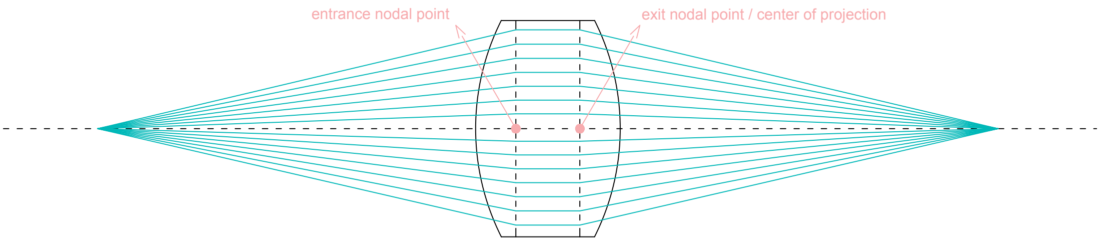
Thin & Thick Lenses

In geometrical graphical analysis, the lens is represented by a **single point in space**, through which all rays pass, in other words, it can be represented as the projection centre. The geometrical model of this type of lens was called the “**thin lens**”, because it was regarded as if its physical dimensions are negligible.

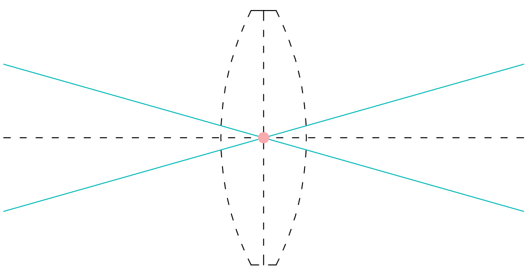
In contrast to thin lenses, **thick lenses** cannot be modelled by this approach: they are characterised by two points, **entrance & exit nodal point**, also known as pupils.

For the purposes of photogrammetry, in the case of thick lenses, the exit nodal point is treated as the centre of projection.

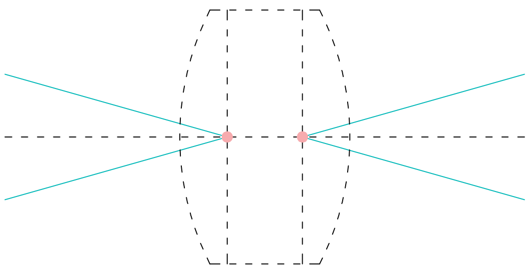




This difference, in terms of central projection model, are schematically described as such:



thin lens modelled as single projection center

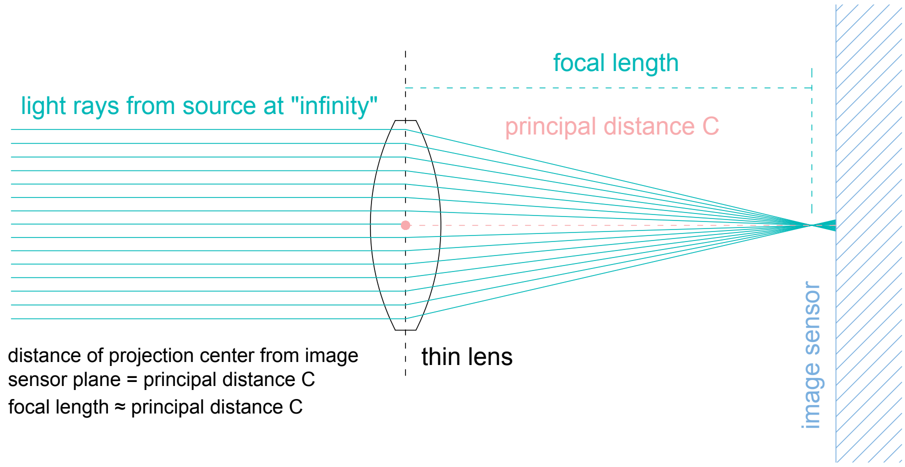


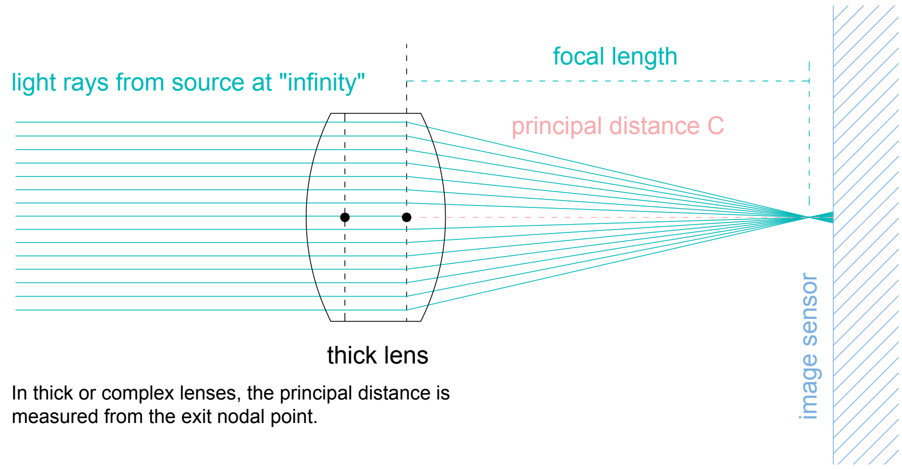
thick lens modelled with entry and exit nodal point

1 http://www.canonrumors.com/tech-articles/all-about-lens-coatings/

Relationship between Principal Distance C and Focal Length

When the lens system is compiled on the photographic camera, the **image sensor plane** is set at a distance **approximately equal** to the **focal length** of the system (as has been measured and specified by the manufacturer). This distance, for the purpose of this presentation can be treated as negligibly small, but it is important to note that these two lengths do not coincide: the principal distance C refers to a length measurement that is defined by the **physical construction of the camera** and denotes the distance of the centre of projection from the image sensor plane, while the focal length is a **constant that describes the optical lens system employed** and denotes the distance over which parallel light-rays (coming from a source at infinity) are brought to a focus(converge).





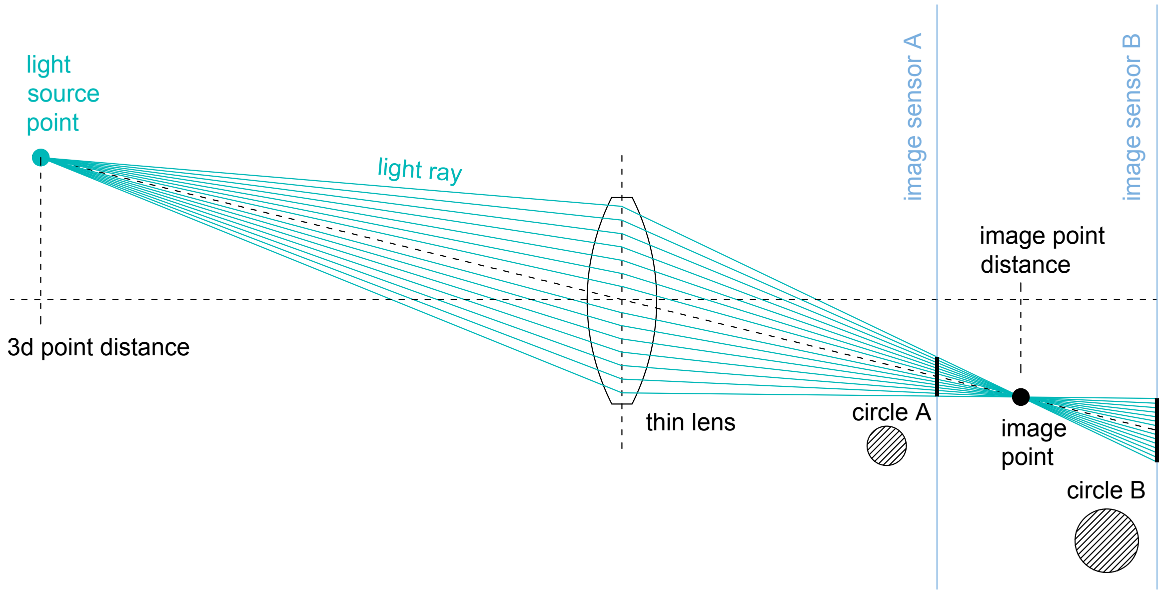
Focal Length & Distance to Image Sensor:

As stated, the **distance of an image point** from the centre of projection is directly related to the **distance of the corresponding 3d point** from the centre of projection and the **focal length of the system**:

$$1/s_i = 1/f - 1/s_o$$

> Given the above, this means that all points regarded as if at infinite distance s_o, have an image distance s_i which is equal to the principal distance c and thus, are **sharply imaged as a point**.

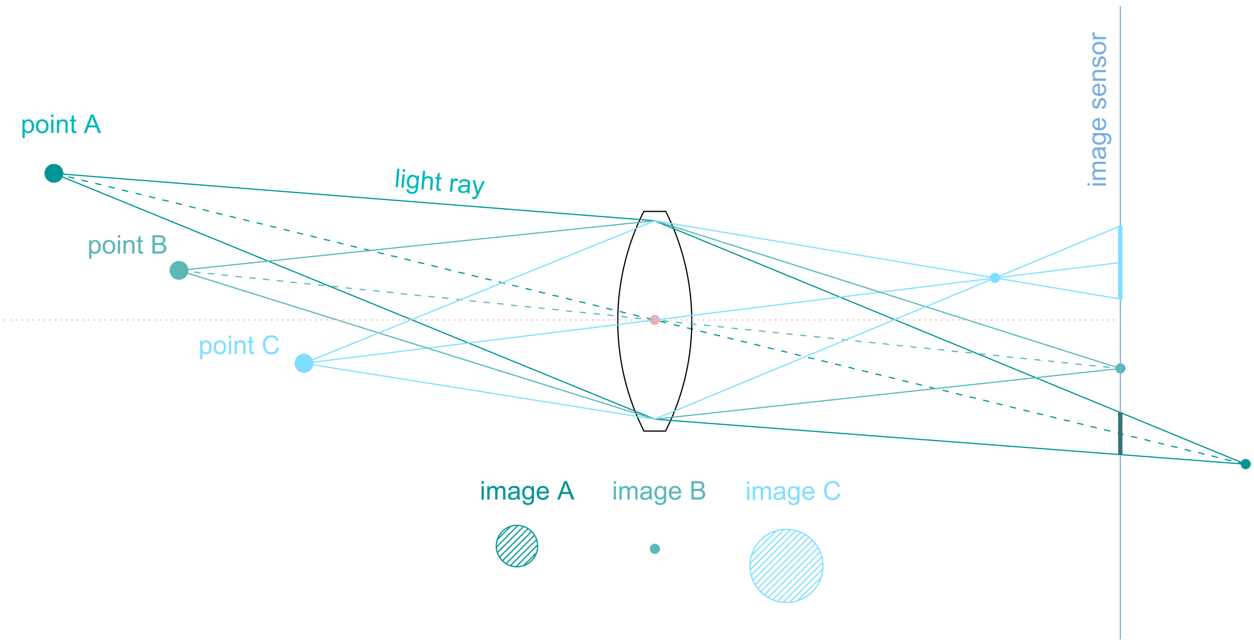
> For all other distances, the light-rays falling/intersecting the image sensor create a circle, termed as **circle of confusion,** whose size depends on the distance of the 3d point.



- Circle of confusion

The **circle of confusion** is an optical spot caused by a cone of light rays not converging on the image plane, but farther away either in front or behind it. It is also known as disk of confusion, circle of indistinctness, blur circle, or blur spot, since a circle of enough size is experienced as **blurriness** in the final image. There is an **acceptable range of circle diameters** that can be treated as if of negligible size and therefore equivalent to a point. This range can be experienced as a sharply-focused point in the final image. All other sizes are experienced as blurriness. The **maximum permissible circle of confusion** depends on **visual acuity** and **image sensor resolution** and their relationship will be presented later on.

> The range of acceptable circle sizes is directly related to the **range of distance deviations** from the **optimum focusing distance** from the centre of projection (for the given focal length).

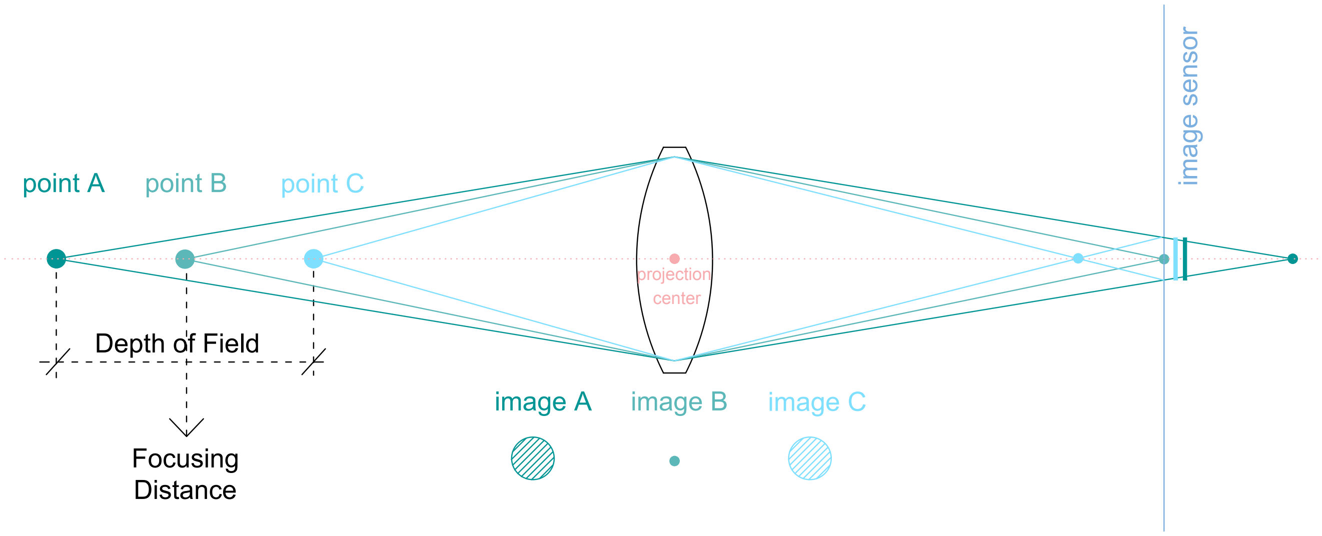


- Depth of Field

This front-to-back zone from the focusing distance is termed **Depth of Field** (DoF) and it describes the distance range in which objects are regarded as sharply imaged. Objects before and behind this distance range form circles of confusion larger than the allowed maximum and are thus imaged as blurriness. The Depth of Field is described as shallow, if this range of distances is narrow, or deep, if the range is greater. Depending on the 3d layout of the scene, this leads to images containing smaller or larger areas of sharply focused objects.

DoF is determined by one more factor, apart from focusing distance and focal length: by the **aperture**

size used at the capturing moment, which will be described later on. It should be noted though that for each aperture size and focusing distance the DoF of a lens system can be clearly calculated.



Focal Length and (minimum) Focusing Distance

Given the above, it would be expected that cameras devices would produce sharply focused objects only for a specific range of distances in 3d space, namely for the ideal focusing distance and the corresponding depth of field.

But as already known, cameras offer the ability to **focus at variable distances**: this is achieved either by minor rearrangements of the lens elements -hence slightly altering **the focal length**- or by adjustments in the lens-image sensor distance- which in turn affects the **principal distance c**.

** This is important to note, since it explains why camera calibration, which will be presented later on is focusing distance-dependent.*

Furthermore, camera lenses are also defined by a **minimum focusing distance**. All objects closer than this distance can no longer be regarded as if at "infinite distance" by the mechanical micro-rearrangements and therefore their s_i is always greater than the principal distance c. This means that their image point is focused farther than the image sensor plane and they are always recorded as blurred spots.

Lens Aberrations

Aberrations are **deviations from the normal/expected behaviour** of the optical device and are observed as **imperfections on the formation of the image**. As opposed to perspective projection, which does not bend lines, aberrations are **deviations from rectilinear projection** (a projection in which straight lines in a scene remain straight in an image). These aberrations, in effect, impose **deviations** on the captured image from the **"accurate" perspective depiction**, as dictated by the **central projection model**.

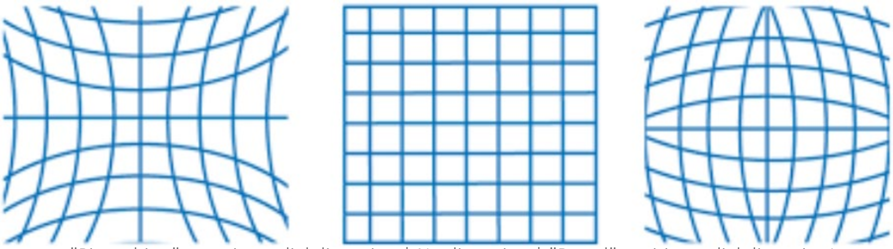
Given that all lenses induce aberrations, the goal is to minimize them, which explains the need for complex multi-element lens systems that balance each others flaws. Lens distortions are commonly **radially symmetric**, since the lens optical systems have rotational symmetry, as stated, namely the optical axis.

The two types of distortion that are of interest to photogrammetry are **radial** & **tangential** distortions:

Radial distortion is caused by the different behaviour of the light rays when they fall on the curved edges of the lens or various lens elements in a complex photographic lens. In effect, it causes minute variations in point scale and it is a radially symmetric effect, which starts at zero at the principal point and increases with increasing distance from it. It is experienced as straight lines appearing as curves and its visual effect is more pronounced near the edges of the image frame.

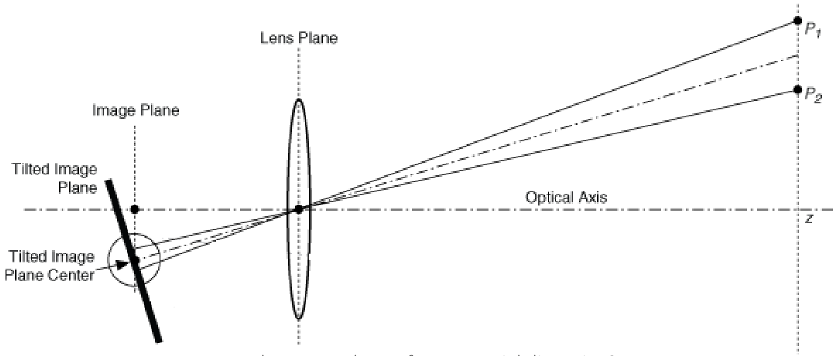
Depending on the focal length of the optical system, radial distortion can grouped in two common categories:

- **Pincushion Distortion**, caused for large focal lengths, where image magnification increases with the distance from the optical axis &
- **Barrel Distortion**, caused by small focal lengths, where image magnification decreases with distance from the optical axis



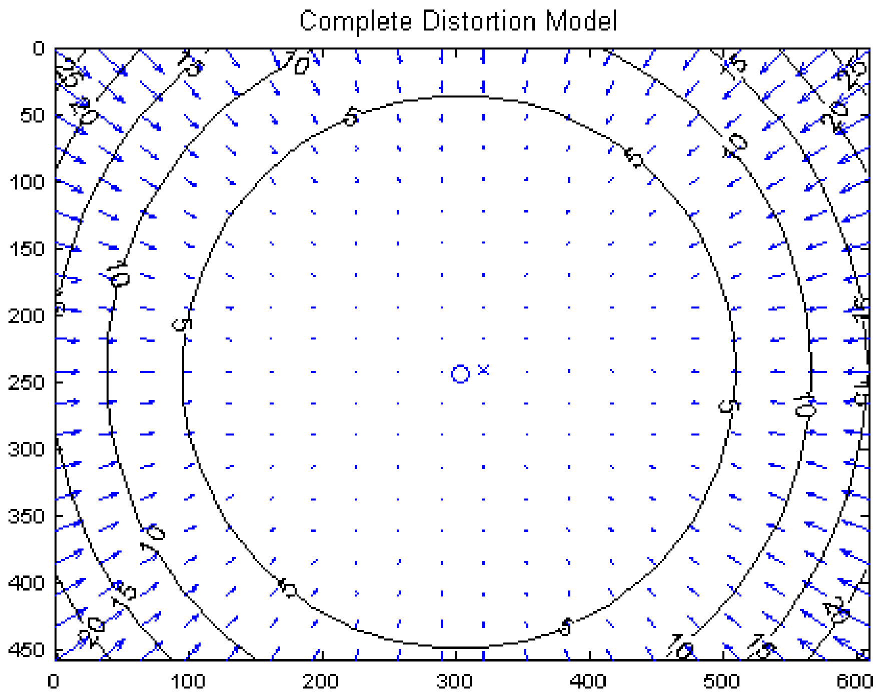
”Pincushion” negative radial distortion | No distortion | ”Barrel” positive radial distortion[1]

Tangential distortions are caused by the physical elements in a lens not being perfectly aligned, also known as **decentreing distortion**.



Explanatory schema for tangential distortion[2]

Both radial and tangential distortion can be determined by the calibration procedure by employing appropriate models, in specific the Brown–Conrady distortion model. Hence they can be corrected analytically at a later stage.



Correction of Radial and tangential distortion via camera calibration methods[3]

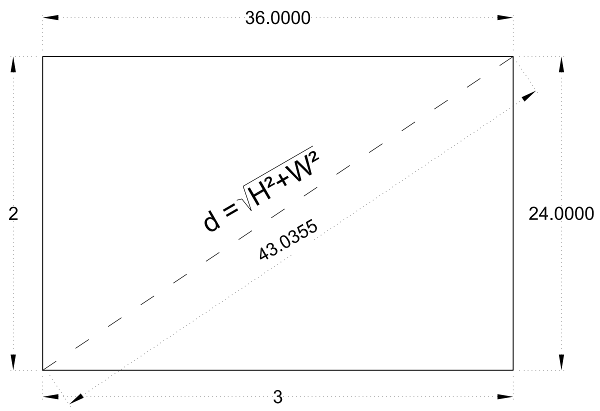
1 lost-contact.mit.edu
2 http://zone.ni.com/reference/en-XX/help/372916P-01/nivisionconcepts/spatial_calibration_indepth/
3 www.vision.caltech.edu

ON CAMERA LENSES

When analysing the properties of camera lenses with regard to the formation of a photograph, the **spatial relationship of the lens - image sensor system** is important. The two primary geometrical aspects of this system are the **size** of **the image sensor**, as well as the distance from the centre of projection, as defined by the **focal length of the lens**.
For this reason, some information about the geometry of the image sensor will be given first.

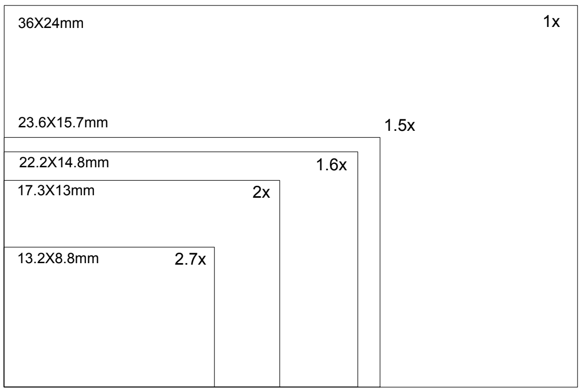
Image Sensor Format

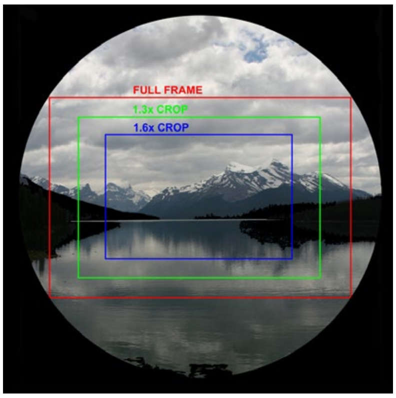
The image sensor format describes the **shape & size** of the image sensor. The predominant image sensor format in digital cameras is termed 35mm, as a reminder of the analogue film era. It denotes a rectangular frame with 3:2 side ratio and physical dimensions of 24 mm × 36 mm. This format is also termed as **full-frame**.



Crop Factor

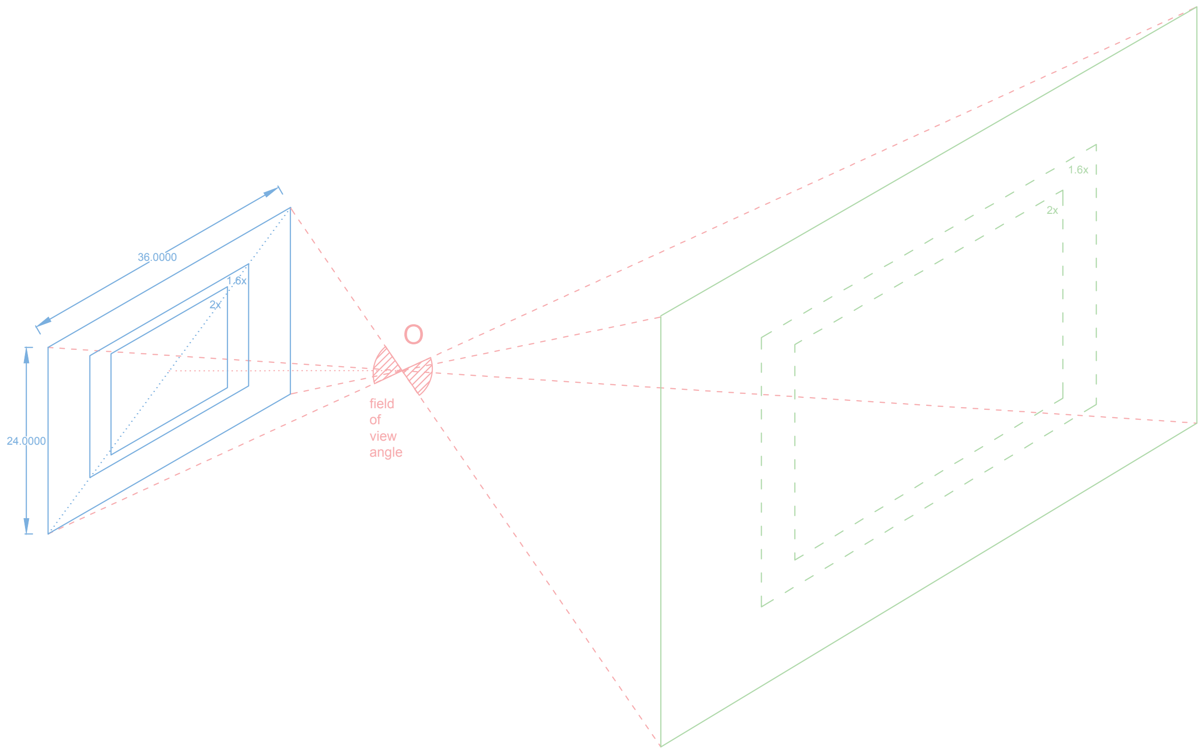
Due to the popularity of the 35 mm standard, all other image formats are described by their size relation to the full frame format. The **crop factor** denotes the ratio of the dimensions of a camera's image sensor compared to the reference format of 36X24mm.





Focal Length Multiplier

The image sensor corresponds to the "canvas". It is obvious that for the same distance of projection centre from the image sensor (defined by the focal length), a different view of 3d space is recorded. Vice versa, it follows that in order to capture the same view, different combinations of focal lengths and sensor formats need to be used. In order to compare lenses with reference to a common format, all lenses are described as if equipped on a full-frame format with regard to their field of view. In order to calculate the effective field of view when placed on a smaller format, the **focal length multiplier** is used, which is equal to the crop factor of the image sensor format. Therefore, when making focal length decisions, the effective focal length needs to be calculated with relation to the image sensor's size.



Comparison of image sensors frames (blue) and their corresponding field of view (green) for a given focal length

Focal Length and Lens Types

The focal length of a lens is a characteristic of primary importance for the formation of an image, therefore camera lenses are categorised exactly on this property on the following types:

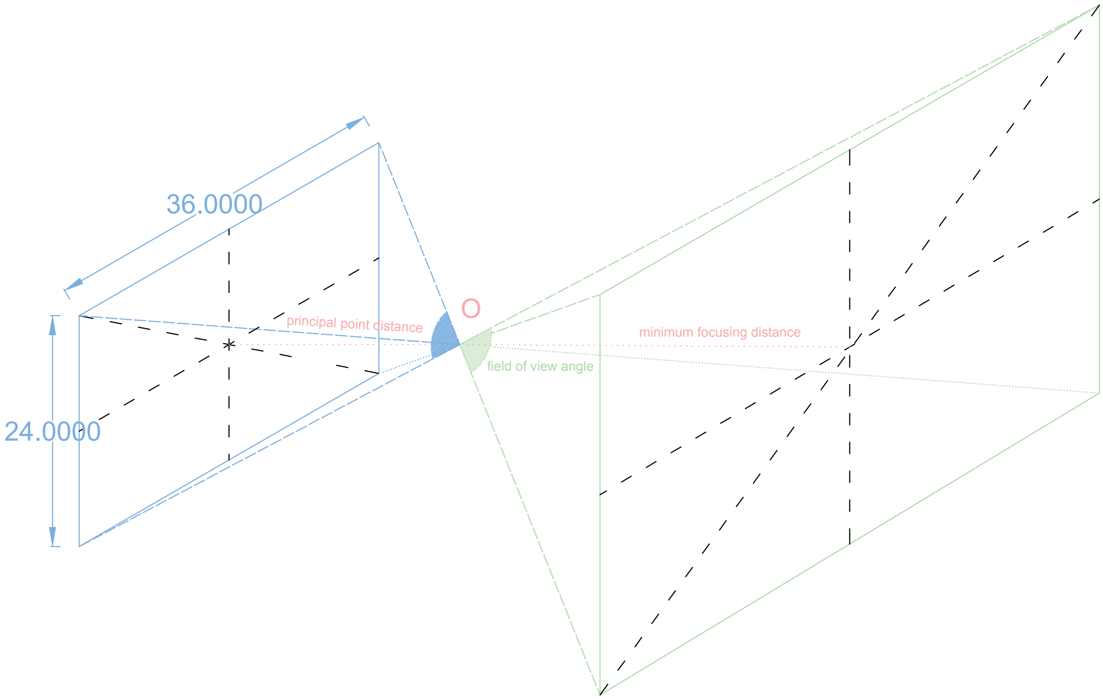
Lens Type	Focal Length
Ultra Wide angle	< 20mm
Wide angle	21mm -35mm
Normal	35mm-70mm
Medium Telephoto	80mm-135mm
Telephoto	135mm-300mm
Super Telephoto	>300mm

** Prime vs. Zoom Lenses*

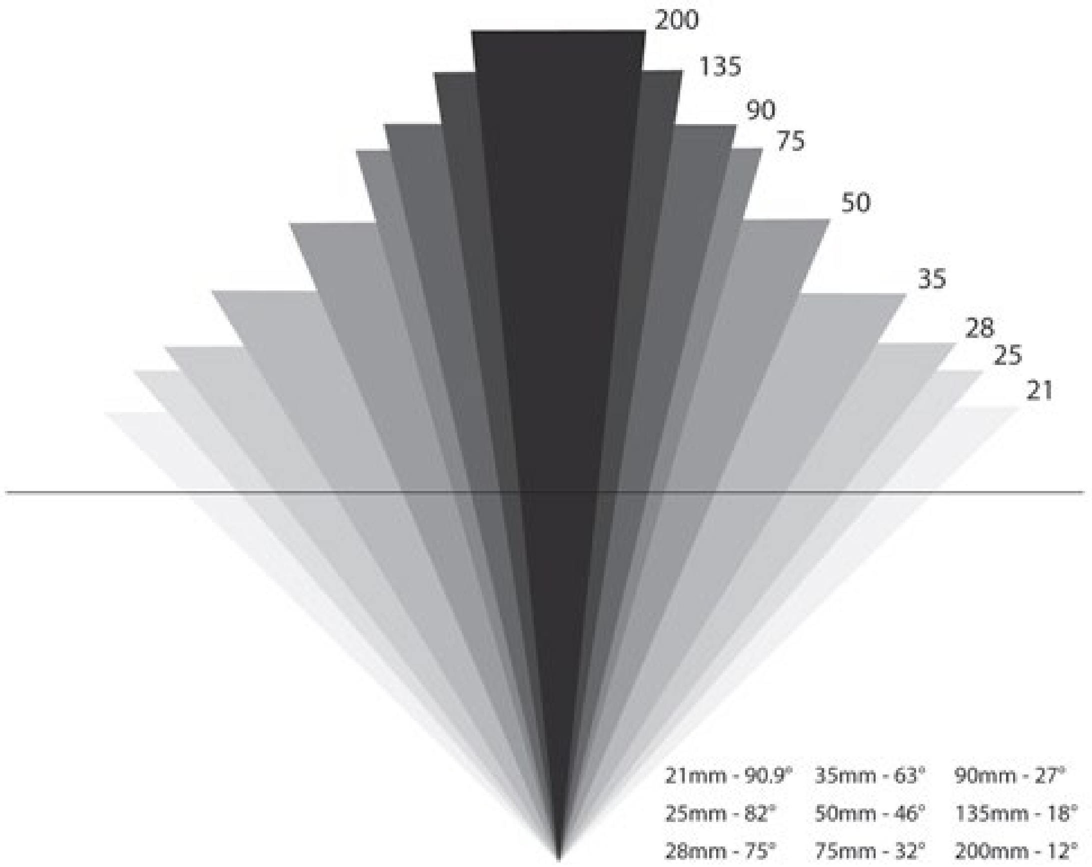
"Prime" camera lenses are complex lens systems with a fixed focal length. As opposed to that, zoom camera lenses are versatile lens systems that can offer continuously varying focal lengths.

Focal Length & Field of View

The focal length of the camera lens defines the angle of the **visual cone of the lens**, also termed as **field of view**. The angle of the field of view is calculated based on the diagonal of the image sensor frame.

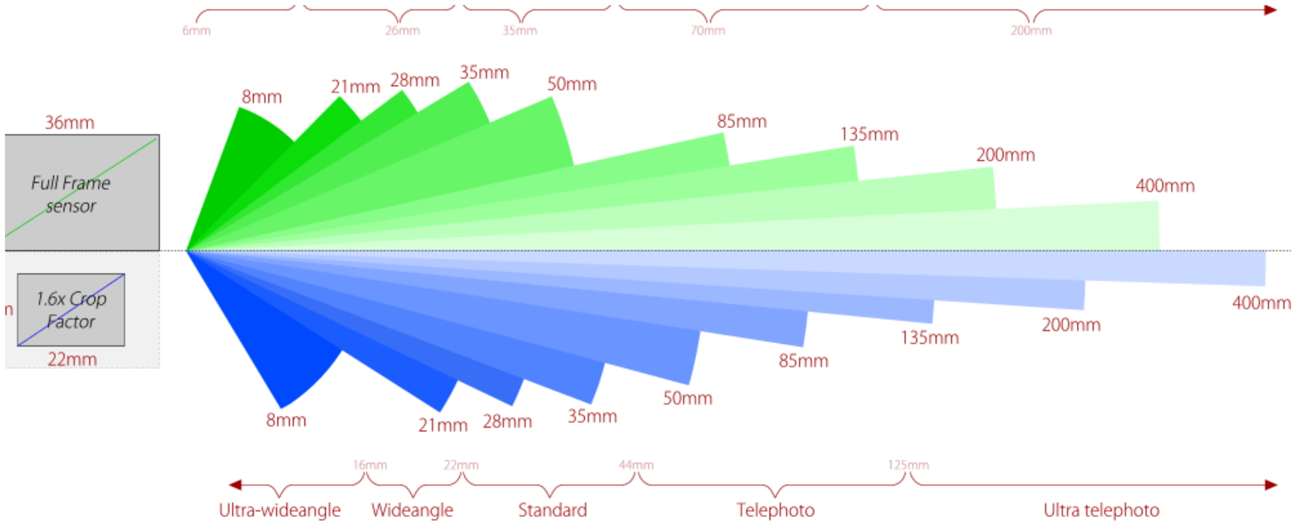


Comparison of Focal lengths and Field of View[1]



1 http://static.photo.net/attachments/bboard/00I/00ICnx-32629384.jpg

Focal Length & minimum focusing distance



Lens types, as illustrated, have different **field of view angles** and **minimum focusing distances**. This combination defines the scene of 3d world that is depicted.

Wide angle lenses capture a wider field of view and can focus on shorter distances. This allows for scenes with great 3d depth variations to be depicted, which is of great importance to photogrammetry.

Note, though, that extremely wide angle lenses, such as the fish-eye lens, which has an opening angle of almost or equal to 180°, cause distortions which are no longer adequately modelled by the distortion correction models and should be avoided for photogrammetric projects.

Tele lenses, on the other end of the spectrum, have a minimum focusing distance that can be relatively large, when compared to the depth distances and configuration of the depicted objects. This will also prove detrimental to a photogrammetric project, since depth cues diminish.

Therefore, the **visual perception of depth** and perspective foreshortening increases with wide angle lenses and diminishes with tele lenses. The perspective depiction of a model works exactly the same way, as has been proven by similar triangles- only the **viewport & image scale** change by changing focal lengths.

III. The Modern Camera

simple camera + shutter + aperture + light-sensitive plate = modern camera

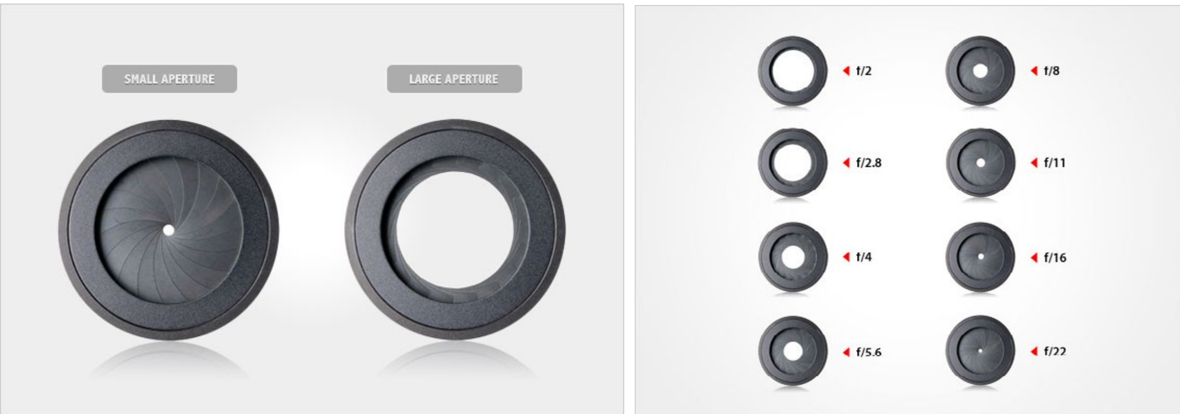
The addition of adjustable shutter and diaphragm completes the birth of the camera. At this point, the properties related to shutter, aperture and image sensor sensitivity (ISO) will be presented and more about the image sensor in terms of resolution will be presented in the next chapter about the digital era.

With the introduction of a light-sensitive “projection surface”, **accurate control of incoming light** is necessary in order to produce a sharp & colour-balanced image. For this reason, the **diaphragm** and the **shutter** are introduced to the modern camera. These two devices can be regulated, based on the **scene’s illumination,** in order to achieve the optimum amount of incoming light. The image formation is dictated by the **intensity of the incoming light** on the one hand and the **sensitivity of the light-sensitive surface** on the other. The combination of the 2 factors define the **exposure** of a photograph.

Aperture Size (f-stop)

The **aperture** is the **opening that determines the amount of light** that is allowed to pass through the lens and falls on the image sensor. Its size is regulated by a device termed as **diaphragm**. The size of the aperture’s opening is measured in **f-values**, which is the ratio of the aperture opening diameter to the effective lens’ **focal length** and is therefore a **unit-less measurement**. It follows that lower values (1.4) denote larger aperture openings and higher values (22) the opposite. Lenses typically have marked f-values, called **f-stops**, which each stop increasing light intensity **by a factor of 2**. An f-value of X is usually displayed as **f/X**.

Since the aperture size in combination with shutter speed, regulate the image sensor’s degree of exposure to light, a higher f-stop (f/22) will require slow shutter speed to ensure sufficient light exposure, while a lower f-stop (f/1.4) aperture will require fast shutter speed to avoid excessive exposure.



Aperture Size and f-stop values[1]

Aperture & Depth of Field

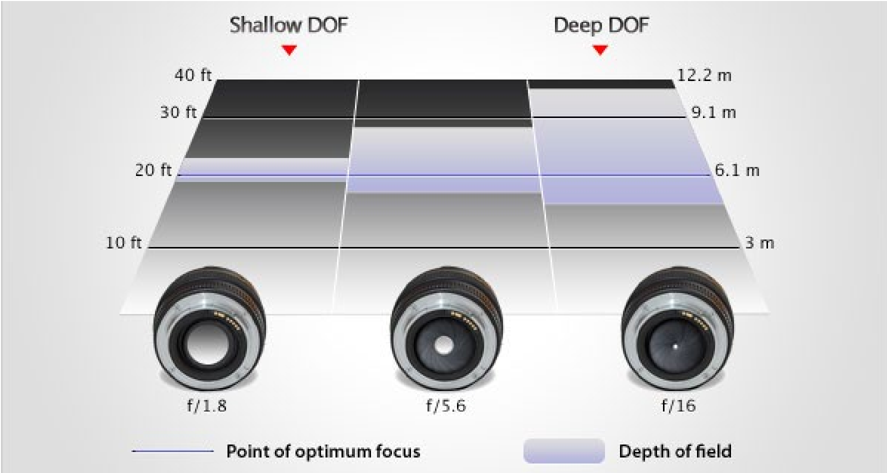
The aperture determines how **collimated[2]/collinear** are the admitted rays, which is of great importance for the formation of the image on the sensor. For a given focal length, **minimizing the aperture opening** will lead to **a greater depth of field**, since only light rays nearer to the optical axis will be allowed, which will be better focused on the image sensor. Minimum apertures can lead to photo blurring, because they require longer exposure time.

> Photographs intended for photogrammetric processing should have the widest possible depth of field, therefore using the minimum aperture opening (maximum f-number) supported by the lens is strongly advised.

1 httpwww.exposureguide.comfocusing-basics.htm
2 Perfectly collimated light is sometimes said to be focused at infinity.

The **optimum focusing distance** as well as the **depth of field** for a given **focal length** can be exactly calculated for **maximum image sharpness**, which is of prime importance to photogrammetry.

Online Depth of Field Calculator:
http://www.cambridgeincolour.com/tutorials/dof-calculator.htm
Free Android Depth of Field app:
DoF calculator



Shutter Speed

The **shutter speed** or **exposure time** defines **the length of time for which the sensor is exposed to light**. It follows that too slow a shutter speed may lead to more over-exposed images, while too fast a shutter speed may lead to unexposed images. Shutter speed is usually set according to **scene illumination** and **target mobility** (it follows that longer exposure time will lead to the creation of blurred depictions for a moving target).

Different combinations of shutter speed and aperture can result to the **same exposure values**: commonly the balance between them depends on the particularities of the occasion.

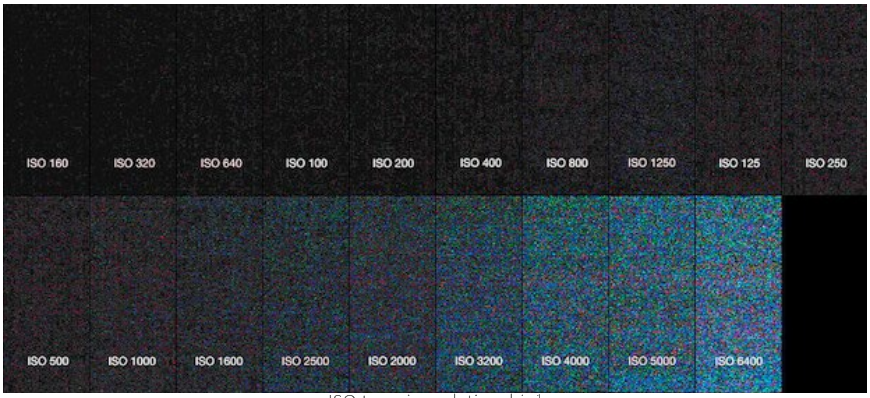
> For the interest of photogrammetry, the factor of primary importance is aperture due to its relationship to depth of field, therefore shutter speed is set according to the chosen f/stop and the scene illumination.

Film Speed/ISO

Film Speed is a measure of the **light-sensitivity** of the **sensor medium**, whether that is a photographic film or a digital imaging sensor. The **measurement scale** is defined by **ISO**[1] and also termed as such. Higher ISO values mean higher light sensitivity and faster exposure speed. The details of the factors that affect light-sensitivity in analogue/digital mediums, as well as the method for the definition of the measurement scale will not be presented. The practical aspect of ISO that is of interest to photogrammetry is its relationship with the **"grain" effect,** also termed as **noise,** that can be observed in photographic images.

> Photogrammetry demands photographs free of noise as much as possible, therefore setting the lowest ISO value allowed by the scene luminance is advisable. To make up for this, even longer exposure time may be needed.

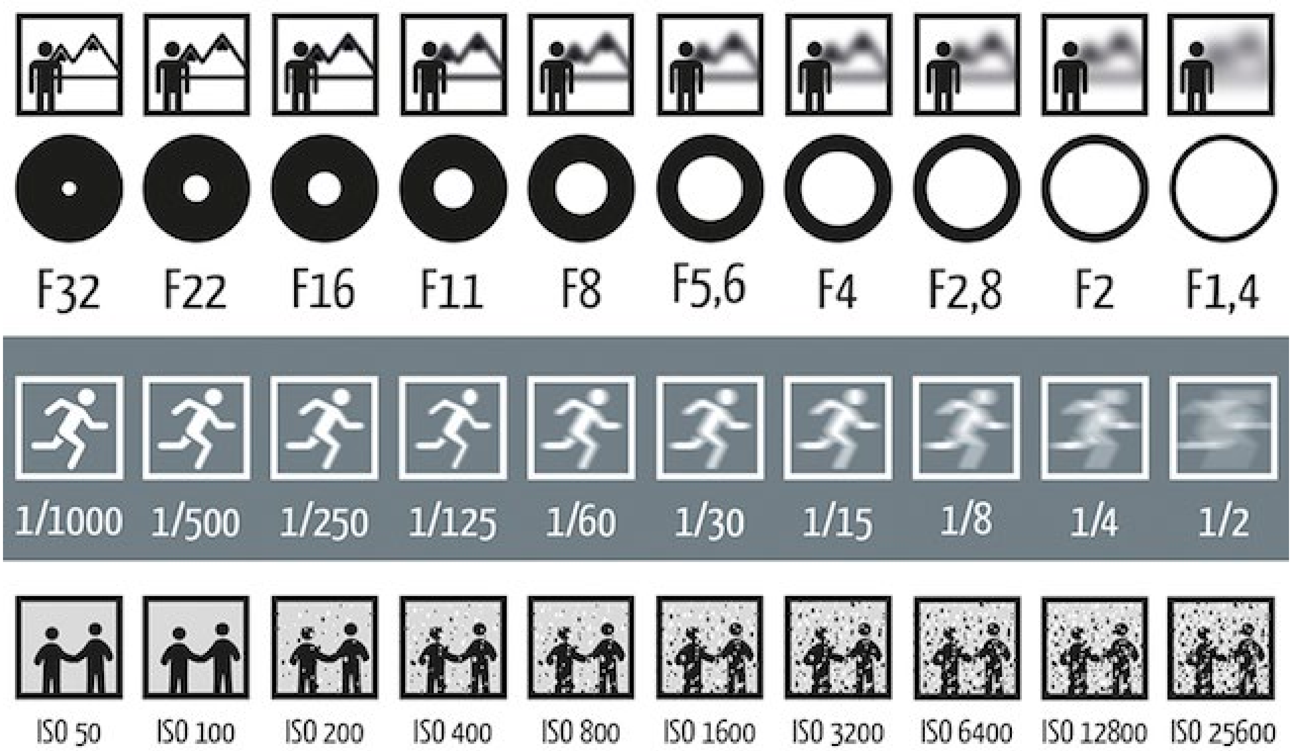
1 International Organization for Standardization



ISO to noise relationship[1]

Summary

The following chart illustrates the relationship between:
- *aperture & depth of field*
- *shutter speed and motion blur*
- *ISO and noise*



In Summary[2]

For the purpose of photogrammetry, the following factors are advised to be set as such:
- *lower f-stops, for maximum DoF*
- *lower ISO values, for minimum grain/noise*
- *long exposure times, for adequate light intensity*

In order to produce sharp images with long exposure times, given the human hand’s instability, the use of a **tripod** is strongly advised.

1 http://bradbell.tv/wp-content/uploads/2011/05/Canon-hdslr-160-iso1.jpg
2 http://lifehacker.com/yup-very-cool-this-foto-cheatcard-was-actually-origin-1699291384

IV. The Digital Camera

keywords: < CCD sensor, RAW file format, Raster Image File>

In the decade 1980-1990, the first commercial digital photographic cameras become available. The new storing type of image data (digital) offers the capability to apply mathematical transformations and filters to the recorded image. Unlike a anologue photographic image, the digital image can be easily radiometrically or geometrically modified.

CCD sensors

Whereas the traditional analogue camera used chemical photo-active coatings on a flat (rigid/semi-rigid) surface in order to produce a light-sensitive plane, the digital camera uses the emergence & conduct of electric charge by means of an important technological innovation: the charge-coupled device (CCD)[1]. Therefore we note a transition of the image sensor device mechanism from a chemical to an electromagnetic one.

CCD architecture, in short

The CCD is in effect the image sensor and has two functions/regions: a photo-active, which is comprised of an array of p-doped MOS capacitors, where electric charge proportional to the light intensity is created by conversion of incident photons into electrons.

The layer beneath is the transmission region, where the created electrical charge from an array is transported to an amplifier and transformed to a sequence of voltages.

After that, the analogue to digital signal sampling of the voltage takes place, the outcome is digitized and stored.

Image Sensor Resolution

CCD sensors, in a way, relate to pixel units of the output image: both are “spatial units” which store information about the light intensity of the “space” they occupy. Therefore, the size of the array of CCD sensors (namely, of the image sensor device) relates to the size of the pixel-matrix (also referred to as resolution) of the digital camera. High image resolution is an important aspect ensuring high accuracy and fidelity of capture, but care must be given to the actual physical dimensions of the light-sensitive sensors. Too small sensor elements are not equally sensitive and tend to produce noise in low lighting conditions, when using high ISO or in dark parts/shadowed areas. Also the inter-spacing of the sensor elements is important with regard to their light-gathering abilities/sensitivity[2].

Greyscale Values to Colour Channels

As is obvious, no distinction of the light wave of the incident rays can occur in the aforementioned process - as is, the result is a monochromatic photograph, with various levels of brightness.

The advance to colour photography comes by the addition of selective light-wave filters in front of each sensor, a concept which in theory is identical with that of colour photography in the analogue era.

Again, the most common combination choice is 3 filters, one for each of the primary subtractive colours: Red, Green and Blue. This is also in direct correspondence with the 3 channels RGB in digital monitors. Each filter blocks out the incoming light rays for all wavelengths apart from those of a designated range, as stated by the manufacturer.

The most common pattern for the distribution of the filters on the capacitator array (Colour Filter Array-CFA) is the Bayer array. In this case, the occurrence of green-allowing filters is twice the amount as that of the red or blue ones, a fact attributed to the high sensitivity of the human eye in the green range of the spectrum.

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1 APS sensors: Recent years have seen a more affordable alternative to the CCD, the active pixel sensor (APS), which is used in most common ubiquitous cameras (smartphone, webcameras, digital pocket cameras and most DSRLs). The APS follows the same principle but with different architecture. The market is dominated by charge-coupled device (CCD) sensors due to their low cost, low noise, high dynamic range and excellent reliability compared to other sensor types, such as charge injection device (CID) and metal oxide semiconductor (MOS) capacitor type sensors.

2 For more information, read : microlens arrays.

**note: Of course, not all image sensors use the same color filters or arrays: what is presented here is simply the industry standards.*

RAW image format

It follows that the image sensor array has information in each sensor element for only 1 channel, whereas the desired output is an image matrix with full information on all 3 channels.

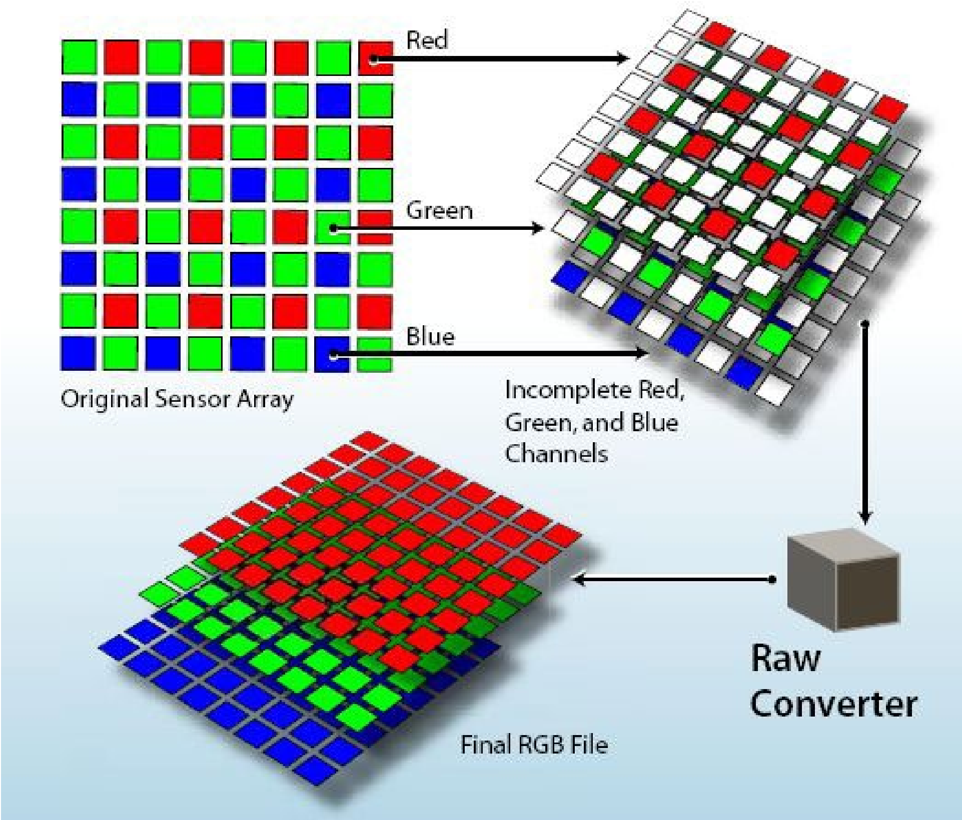
This unprocessed information is stored in a yet incomplete file format, the “RAW” file, sometimes also called as a “digital negative”. It is called so because it is yet unfit for previewing or editing in image processing programs, but contains the information necessary to produce the visible image. RAW, as well as DNG[1], are considered as digital negatives, since they contain almost unprocessed data coming directly from the camera sensor and preserve the most amount of colour information about an image with comparison to other formats. In addition to the basic exposure information, RAW files also store other camera-specific data such as focus point, picture controls, etc.

RAW is a proprietary format that is tied to the camera manufacturer and sensor, and therefore is not supported by all software products, but RAW files are fully supported by their manufacturers and therefore work with camera-specific software packages.

** It follows that RAW files contain accurate radiometric information about the scene that in following stages is compressed and lost. Therefore, under specific occasions, handling RAW files can offer multiple benefits.*

Demosaicking

The process to “fill in the missing blanks” of the Bayer array and create a full 3-channel matrix is called demosaicking. It is achieved by interpolating the final values with the help of the neighbouring pixels, namely, by overlapping arrays of 2X2. As a result, there is a loss in resolution, that varies according to the method applied. The demosaicking process can occur internally, by the firmware integrated in the digital camera model, or externally, by a software program of the choice of the user (sometimes also called, “developing”, following the film photography analogy).



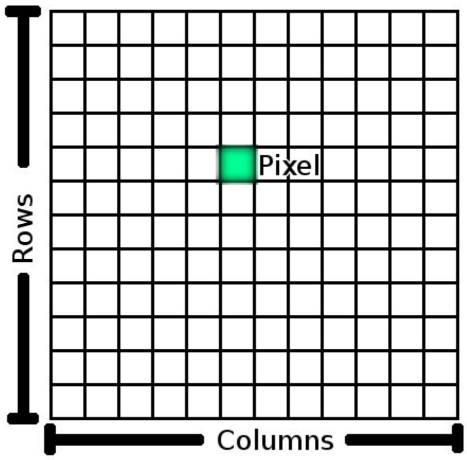
Bayer array in sensor, 3 incomplete colour channels, Raw conversion algorithm and final RGB raster file[2]

1 DNG is Adobe’s proprietary image standard that was created to store image data in a generic, highly-compatible format.
2 http://www.letsgodigital.org/en/18008/raw-image-processing/

The Digital Storing Format:

Raster Files
The digital outcome of the RAW conversion process is a raster image file, namely a matrix of units each containing radiometric information about the light's intensity for all 3 colour channels of the image sensor. The raster file is a scale-less rectangular grid, which can be displayed at any size. For the purpose of this presentation, a raster file's main attributes are its **resolution,** its **colour space** & its **bit depth**.

Pixel
The **pixel** (picture element) is the **repeating unit of the raster file's matrix**. Each pixel is identified by its **location** on the rectangular grid and is **attributed** with the **values of light intensity** at that particular image location for all the colour channels of the given colour space.

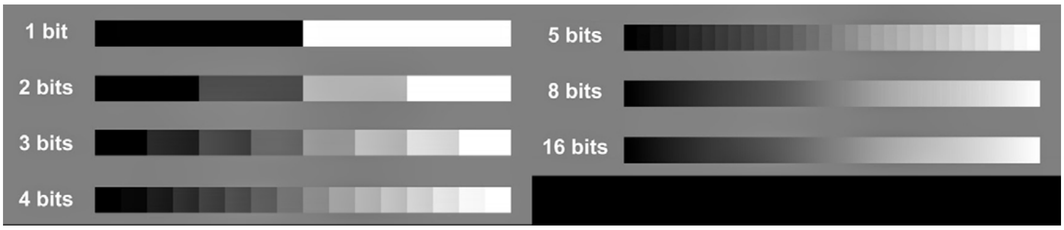


Illustrative sketch of a Raster Files matrix[1]

Raster Image Resolution/Pixel Size
The dimensions of the matrix are given as the **number of pixel rows and columns**. Sometimes, raster images are also described by the shear amount of pixels they contain (columns*rows). This is a common marketing occurrence for the description of camera image sensor resolutions.

Radiometric Resolution / Bit Depth of a digital Image
A pixel in a RGB colour space stores information about the intensity values of the three primary colours: red, green, and blue. The intensity value of each is stored as an **8-bit value per channel**, translating into 256 different intensity values for each primary colour. The amount of bits used to describe the value of an attribute is also called **bit depth**, since the amount of bits is directly related with the amount of possible values. When all three primary colours are combined at each pixel, as many as 256^3 or 16,777,216 different colour hues can be described, a range also termed as "true colour." Sometimes, this is also referred to as a 24 bits per pixel radiometric resolution (3 channels * 8 bits). It should be noted that images with higher bit depth, such as 16 and 32-bits can also be recorded with specific cameras. The **32 bit depth**, though, offers more colour information than most systems can represent or the human eye can detect as separate hues. These images are usually remapped on a lower bit depth for viewing and management purposes and offer the benefit of better colour accuracy.

1 http://docs.qgis.org/2.0/en/docs/gentle_gis_introduction/raster_data.html



Bit Depth and Amount of Values that can be represented[1]

Compression and image file formats

Most raster images are stored in file formats that employ **compression algorithms** to **decrease file size** and **facilitate image manipulation**. This compression leads to an **inevitable loss of colour information** of **variable degrees** depending on the method and extent of compression.

Therefore, raster image file formats are divided in two main categories: **compressed/lossy** & **uncompressed/lossless** file formats.

The most common compressed format is the **JPEG format**, which can typically achieve a 10:1 compression with little perceptible loss in image quality and is ideal for viewing purposes.

The most common lossless format is the **TIFF**, which is the mainly accepted standard high image quality demands, such as printing tasks or scientific digital image analysis.

> For a photogrammetric project, dealing with TIFF files is advisable if enough computational strength is available.

Image Metadata / EXIF

Metadata is term that denotes “**data that describes other data**”. In this case, a photograph’s data is comprised of colour information, while its metadata relates information about its “creation” / capture. Such information includes camera model, capturing time (even location if supported by camera), shooting settings (f-stop, shutter speed, ISO, exposure value, etc), file properties (image resolution, colour space), etc. **EXIF** is the **standard** that describes how the metadata information is structured and presented.

> For the purpose of photogrammetry, valuable information can be derived from the EXIF metadata, since photogrammetry needs detailed and in depth knowledge about the capturing “event” of the photograph.

1 http://www.the-working-man.org/2014/12/bit-depth-color-precision-in-raster.html

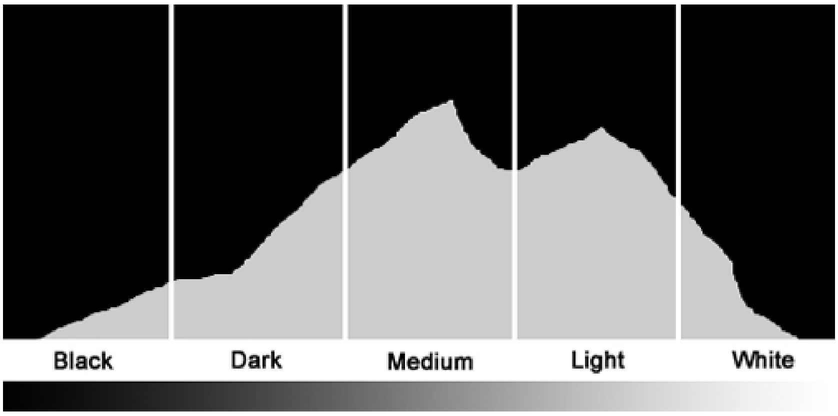
Digital Image Manipulation Processes

One of the main benefits of storing colour information in digital format is its **versatility**. A great variety of operations can be performed on raster images that transform the original data into new visual outcomes. When dealing with photographs, this means that **drawbacks of the original photograph**, imparted at the time of capture, **can be amended later**. A correction process might include operations, such as exposure correction (histogram stretching), colour balance, noise reduction, sharpening, etc.

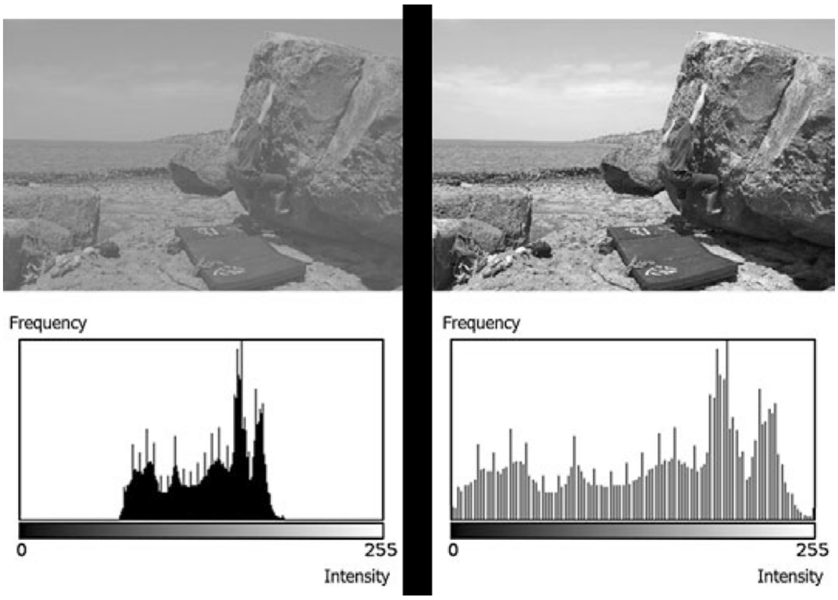
> This is especially important to photogrammetry, since it can increase the "readability" of an image by the human eye in a manual photogrammetric procedure.

Furthermore, digital images open the way for **image analysis by computer vision algorithms** that allowed for the **development of automations in photogrammetry**, a factor of prime importance.

> When dealing with photographs that are intended for an automated workflow, manipulation of the colour information of the images should be performed with great care and only with deep understanding of the algorithm involved, since an increase in human visual perception does not coincide with optimization for the involved computer vision algorithms.



Histogram: a graphical representation of the tonal distribution in a digital image. [1]



Example of Histogram stretching[2]

For more information about digital imaging, please visit Digital Image Dictionary"
http://www.dpreview.com/glossary

1 http://seeinginmacro.com/wp-content/uploads/2013/07/histogram-example.jpg
2 http://what-when-how.com/wp-content/uploads/2012/07/tmp26dc100.png

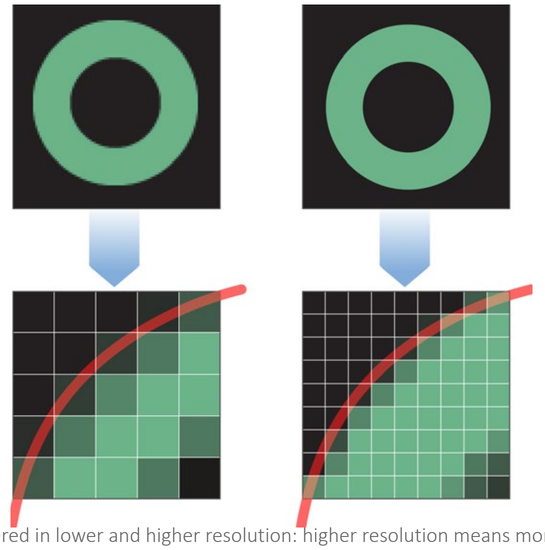
RESOLUTION

General Term Definition

Resolution is a versatile term that can be applied to any suitable **medium to represent its information holding capability**.

Image Resolution

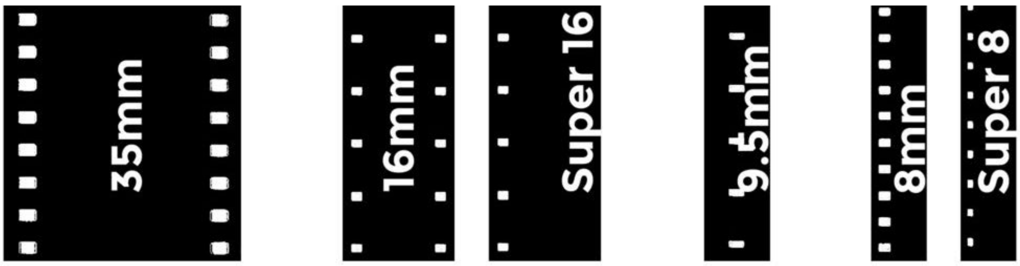
When applied to images, resolution[1] denotes the "**descriptive power**" of an image. The same content rendered in two images of different resolutions will contain different **amounts of information**, resulting to according **levels of detail**. Higher resolution mean more descriptive power, thus more **accurate depiction** of the target.



The same content rendered in lower and higher resolution: higher resolution means more "descriptive power".[2]

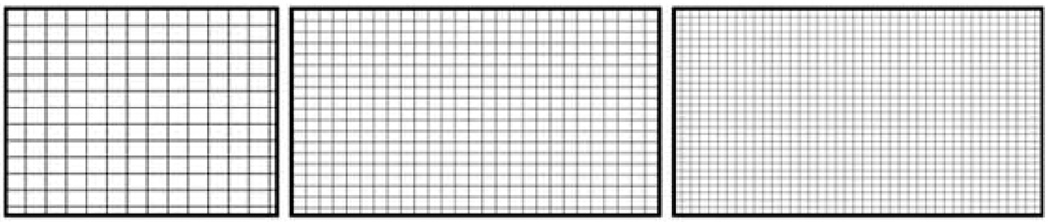
Resolution is determined by the **amount of data-holding (resolving) units of the medium**.

> In **analogue film photographs**, the term resolution refers to the **physical dimensions** of the medium, i.e. film.



Film Format Comparison[3]

> In **digital images**, resolution is described by the **size of the data structure, i.e. pixel matrix**.

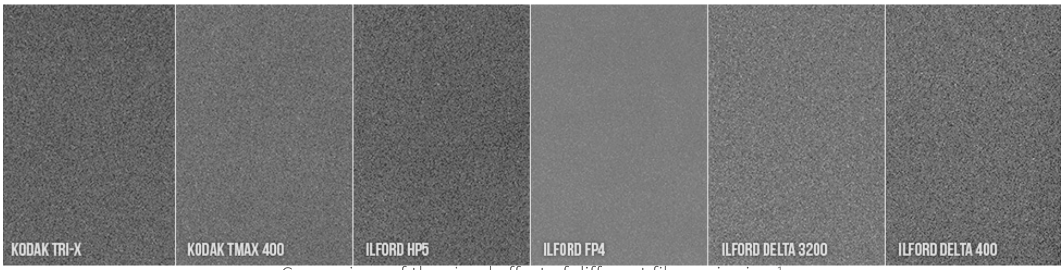


Matrix Sizes: 640x480 pixels > 1280x720 pixels > 1080x920 pixels

1 Sometimes, the term "resolution" is used interchangeably with the term "level of detail".
2 https://developer.apple.com/library/mac/documentation/GraphicsAnimation/Conceptual/HighResolutionOSX/Introduction/Introduction.html
3 https://psap.library.illinois.edu/format-id-guide/film

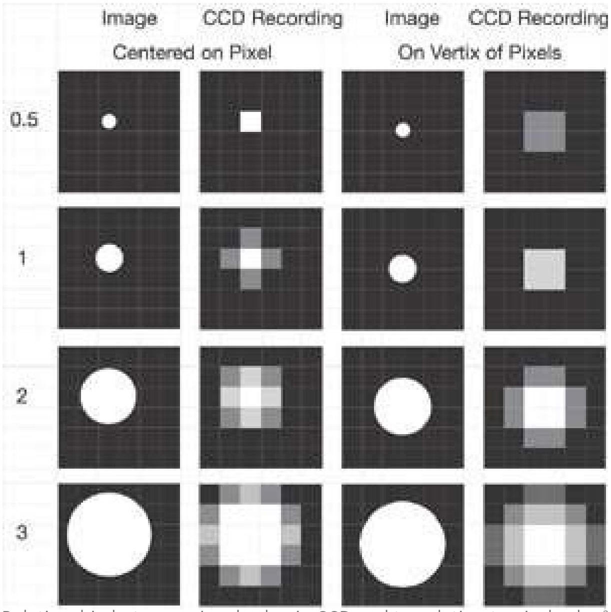
Resolving Unit

> In analogue film photographs, the smallest data-holding unit would be defined by the **size of light-sensitive crystal**. This property is directly connected with the stated **ISO value** of the film and is experienced as the amount of “**grain**” of the film.



Comparison of the visual effect of different film grain sizes[1]

> In digital photographs the spatial resolving unit is the **CCD**: the CCD, much like the silver halide crystals of analogue films, is the **light-sensitive sensor** that “reads” the incident light’s energy levels. After the analogue to digital conversion by sampling, this signal is translated in bit-values and stored in the pixel data unit. Since the CCD can be viewed as the **physical “precursor” of the digital pixel**, camera manufacturers state the image sensor’s resolution indirectly by means of the max. resolution of the produced photographs. *Therefore it should be noted that “CCD sensor size” is commonly used interchangeably with “pixel size” and “(camera) sensor resolution” with “image/photograph resolution”.*



Relationship between signal value in CCD and translation to pixel value[2]

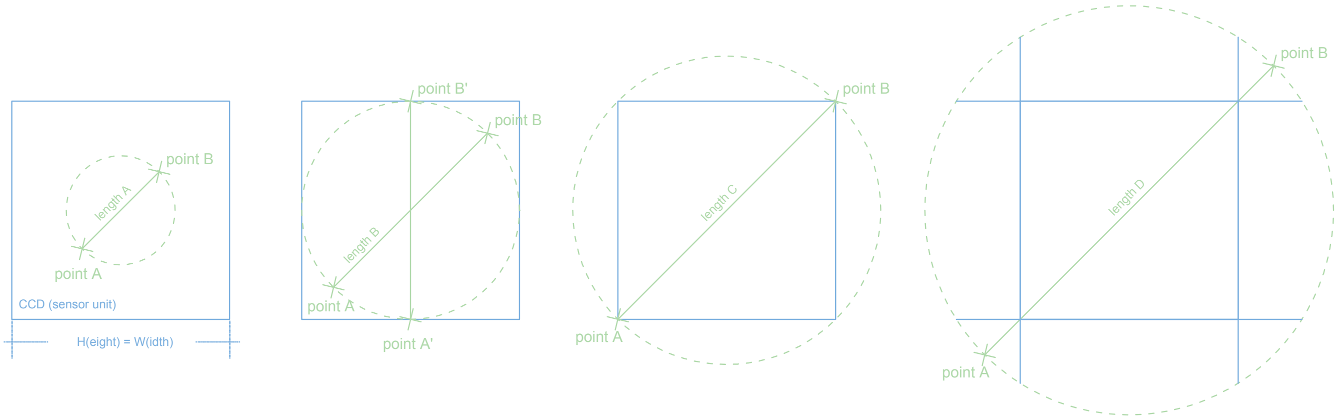
Resolution limit

The **resolution limit** of an imaging system denotes **the spatial size of the imaging system’s unit,** therefore **the smallest size that can be recorded or depicted.**

In the case of the digital photographic camera, this is the **CCD sensor size** (as stated also commonly referred to as pixel size). In specific, any 2 points in space will definitely be imaged as separate points by the camera, as long as their in between distance is at least equal to the CCD size (width or height, given square CCD formats).

1 http://itipix.com/Images/ArticleImages/InlineImages/104501-film-grains-ORG.jpg
2 http://www.andor.com/learning-academy/ccd-spatial-resolution-understanding-spatial-resolution

> > Since a camera’s CCD sensor size is usually not stated in technical specifications, this value can be easily calculated by knowing the image sensor’s format and the image resolution it supports.

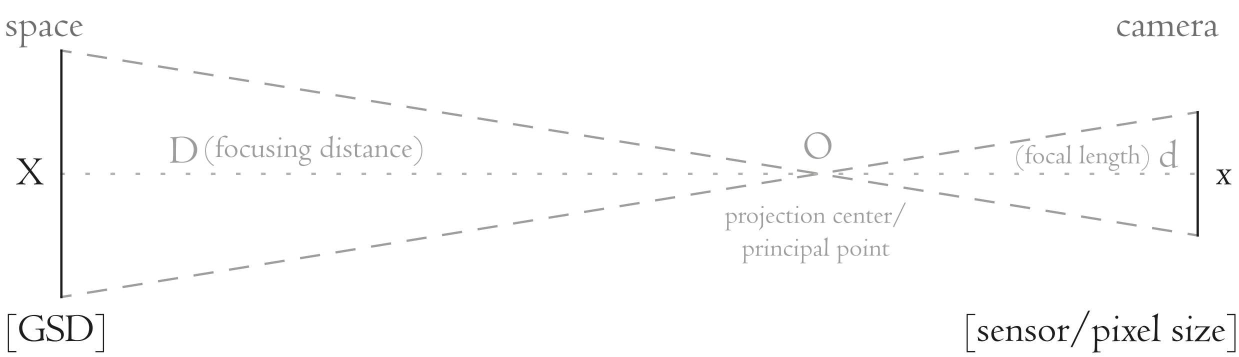


Two points can surely be recorded if their distance is equal or larger than the square sensor’s size

Resolution Limit of an imaging device with reference to Photogrammetry

> Ground Sampling Distance

For a given **photographic scale**, this **smallest recording length** (the CCD sensor element dimension), translates to a **smallest recordable length**[1]: this length is known as **Ground Sampling Distance**. Since the photographic scale is focal length and focus distance depended, the following equation describes the relationship between all of the above factors:



*GSD = Photographic Scale * Pixel Size* > $X = k * x$
Photographic Scale = Focusing Distance / Focal Length > $k = d/D$
> $X = d/D*x$

Therefore, GSD depends on **focal length of lens**, **focusing distance to target object** and **camera’s CCD size**, which in turn is calculated based on **image sensor format** & (max.) **image resolution**.

> It follows that with the same equipment, different depth-planes are characterized by different GSDs.

1 As is perceived by the given viewing angle.

SCALE

Drawing Scale

In a more traditional line of thought, where typical photogrammetric products are 2d plans/elevations (drawings), as well as orthophotos (images), the notion of **drawing scale**[1] plays a very important and straightforward role: drawing scale defines **the factor by which the drawing represents reality**, just like photographic image scale denotes the factor by which the photograph represents .

k = h/H, where:

Drawing scale = k, Measurement on drawing= h & Measurement on object= H

> To calculate actual lengths from measurements on drawing: H =h/k.

Level of Detail according to Drawing Scale

Secondarily, drawing scale defines the **level of detail** of the drawing itself, meaning the **size of the smallest feature** that can be depicted. In hardcopy outputs, the smallest "depiction" size was defined by **visual acuity**, by the perception (**resolution limit**) of the human eye. This was set by experience[2] at **0.25mm**. Depending on the drawing scale, this length represents different actual physical lengths.

*For example, in a drawing in 1:50 scale, the smallest perceivable unit of 0.25mm would represent (0.25*50 = 12.5mm =)1.25 cm, while in a drawing of 1:100, it would represent a length of 2.5cm.*

This means that any physical detail/feature of the object with length larger than this threshold **should be represented** on the drawing- any detail with smaller size **should be omitted**.

> Thus, the level of detail of the specific drawing scale is defined.

In the **digital era**, drawing files are stored in vector format, bringing a large "turn-about" in the way the notion of drawing scale is perceived. 3d CAD space is approximated as "infinite" and continuous: zooming in and out (changing viewing scale) has theoretical no limit. Therefore, no physical boundaries define the drawing scale at the time of drafting the plans, only **clear understanding** of the appropriate "level of detail". For digital workflows, the smallest length used, again set by experience, is **0.1mm**.

Photographic Scale

For the interests of photogrammetry, a photographic image is a **scaled drawing** of the physical object. The scale of the depiction is directly related to the object's distance from the sensor. Each depicted object/point has its own scale depending on its distance (**point scale**) and therefore a single photographic image contains elements in various scales. If the elements are in comparatively near distances from each other compared to the distance from the camera, then the photographic image can be characterised by an **"average" image scale**. For the purpose of this presentation, this will be from now on referred to as "**photographic scale**.

Level of Detail of Photograph

Given the fact that a photograph for the purpose of photogrammetry is a primary input that will be transformed into a **source for valid measurements** -like a map or a 2d drawing plan-, the notion of "drawing scale" and "level of detail" applies again. By knowing the photographic scale, one can calculate the size of the smallest feature that should be recorded by the imaging system. *(For example, for a photographic scale of 1:50, the smallest feature to be depicted should be 5mm given a 0.1mm threshold.)*

If details of this size can be recorded, then the photographic image is **true** to its **photographic scale** & to the **corresponding level of detail**, thus offering the required amount of information.

> Whether an imaging device can support the necessary level of detail for a desired photographic scale, depends on the imaging systems resolution.

1 The term drawing scale will be applied here on orthophotos too, since they can be treated as a metrical background, as a "map" product. By using the term "drawing scale", we wish to differentiate from the term "image scale", which in analogue images/photos would refer to their physical dimensions and in digital images would refer to their matrix size.

2 Also, by scientific basis, for more information on this, see appendix "Human Eye: spatial resolution".

Comparing (Imaging System's) Resolution to (Photographic Image) Scale

> If the GSD attained by the specific set-up is equal or smaller than the **length of the smallest feature**, as demanded by the **desired photographic scale**, then the imaging system has enough resolution to support the **required level of detail**.

Therefore, *GSD < smallest physical feature, required by level of detail*

In other words:

*Resolution limit of recording medium * recording scale ≤ Resolution limit of depiction medium * depiction scale*

Organizing a Project:

- *State desired Drawing Scale of Output*
- *Calculate Level of Detail for the desired scale (LoD)*

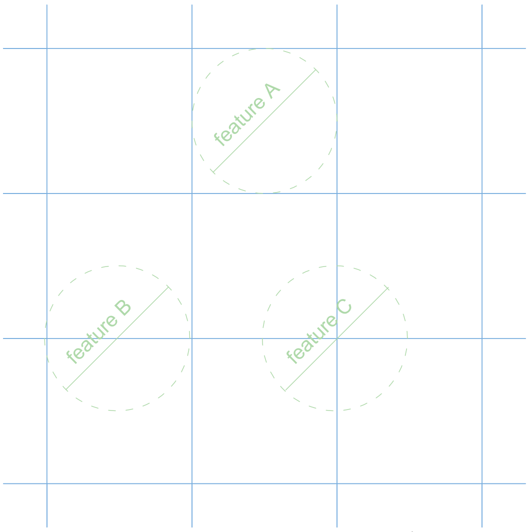
- *Calculate Photographic Scale of Input images*
- *Calculate Ground Sampling Distance (GSD) for average or point scale, as needed*

- *Check, if GSD < LoD*

ACCURACY

Accuracy

At the same time, the smallest feature that can be measured on a drawing or image, apart from the level of detail, also represents the **accuracy** of the drawing/image, which is especially important in cases of **documentation** (as an alternative to designing from scratch). Any point on the drawing/image has an "uncertainty" about its location equal to this size. For the purposes of photogrammetry, this location uncertainty translates into an uncertainty in the direction of the ray that is projected from that point, through the perspective centre, into the scene. Multiplied by the point scale, it results in uncertainty in the location of the point in 3d space.



Uncertainty of location of the smallest recordable/imaging feature

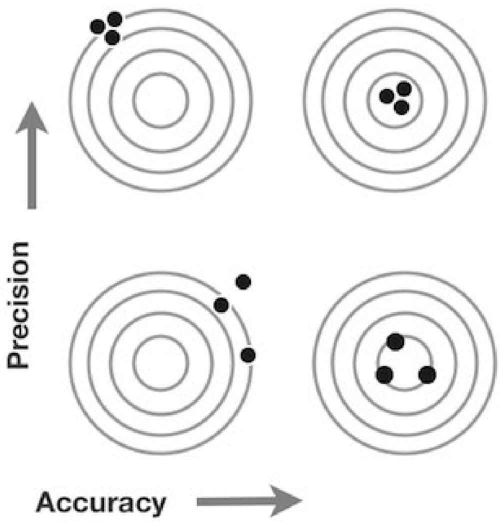
Distinction between accuracy & precision

Accuracy is a term that describes the **degree of closeness of a measurement to its real value**. Thus, an accurate measurement is also defined as a **true measurement**.

Precision is another related term, that describes the **level of consistency of results**, given repeated/multiple measurements. Precision is associated with the concept of "random error" and is involved in application of instruments or processes. Thus, a precise measurement is a **consistent measurement**.

Since inconsistent measurements in a documentation process affect the accuracy of the output, the term **accurate** is sometimes used to denote both true (**no systematic errors**) and consistent (**no random errors**) results.

The following sketch clarifies their difference:



Photography Chapter: Closing

In this chapter, something of a **historical overview** of the **evolution of the photographic camera** was employed, in order to present **knowledge-bits & mechanisms** that are **integral to photogrammetry**.
The overview was performed by means of **4 “marking points”**: the pinhole camera, the simple lens camera, the modern camera & the digital camera. By this method, the properties that arise at each evolutionary “stop” are presented **step by step, each set stacking on the former**.

Summary Points

In pinhole camera:
- Explanation on why the central projection model can describe the photographic image creation process
- Presentation of the exact way that 2d snapshots of 3d space are created by employing the central projection method
- Understanding of the spatial relationships between the elements of central projection (P.centre, P.Plane, 3d Point), with most important, the establishment of the notion of scale between object and depiction.

In simple lens camera:
- Presentation of the new factors of the image formation mechanism that arise with the introduction of the lens device
- Explanation on how a photograph can diverge from the clear abstract model of central projection due to the lens properties
- Presentation of the spatial relationship between lens and image sensor with regard to the field of view and perspective depiction

In modern camera:
- Presentation of the camera-related parameters (aperture, shutter, sensor sensitivity) that further affect image formation in terms of quality
- Rating of their contribution to the final image with regard to the purposes of photogrammetry

In digital camera:
- Presentation of the way/s that information is
  captured & digitized (CCD sensor)
  translated (RAW conversion)
  stored (raster files)
  compressed (file formats)
  described (metadata)
  & manipulated (image editing & analysis)
- Understanding of the fact that pixel colour information acts as the “structural unit” of the digital photograph’s data structure.

About resolution of imaging systems and metric references:

Finally, since the photograph is intended as a metric reference, the **notions of scale & accuracy** were laid out, as well as the notion of **resolution**, all of which describe the amount of information that a photograph can contain about an object. Understanding was provided on the **interrelation** of scale with the resolution of both the sensor(recording system) and the image(data format).

Now, all these elements can be combined to provide an insightful background for understanding in theory (and in the next section, performing) a photogrammetric task.

PHOTOGRAMMETRY

Photogrammetry aims to reclaim the **latent 3d spatial information from photographic images** in order to achieve **3d point restitution**. Photogrammetry treats the **camera** as a **measuring instrument** that records **directions of light rays in space** and the **photographic image** as **metric reference**.

1) starting… from photographs

Photographs can be seen as the primary pieces of photogrammetry's "puzzle". Photographs are perspective & distorted 2d snapshots of coherent 3d space - each, a separate planar surface.

> Photogrammetry's aim is to re-combine these pieces in a reverse engineering attempt to reconstruct the 3rd dimension. The first task is to "rise" from the 2dimensional world of the photographic planar surface to 3dimensional space.

2) converting…to bundles of light-rays

This is achieved by relating the photograph's plane to the geometry of the camera that captured it.

The 3d spatial relation of the photographic plane & the centre of projection allow the reconstruction of the bundle of light-rays that originally formed the image.

Each of the rays originates from the centre of projection, passes from each image point and extends indefinitely in 3d space. In this "space", therefore, only the relative location of point-pairs is of importance: between the centre of projection and each image point.

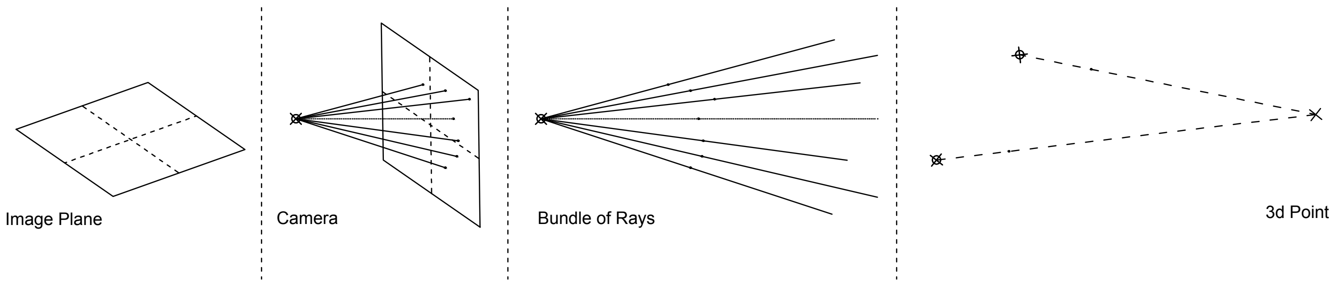
Thus, the initial, flat pieces of the puzzle attain one more dimension and the puzzle's pieces now -photograph & camera- can be treated as "3d bodies".

> Photogrammetry's next task is to reposition these pieces in 3d space in their original location and orientation at the time of photo-shooting.

3) ending… with 3d points

When this is achieved, 3d point restitution is complete: the intersection of the homologous light rays from neighbouring bundles/photographs define the location of the imaged point in 3d space.

>Out of the interconnections of its 3d points, the shape of the 3d object is described.



Coordinate systems

Thus, it is clear that in order to solve the reconstruction "puzzle", photogrammetry deals with 3 separate "spaces" that need to be unified, with each "sub-space" containing the former:

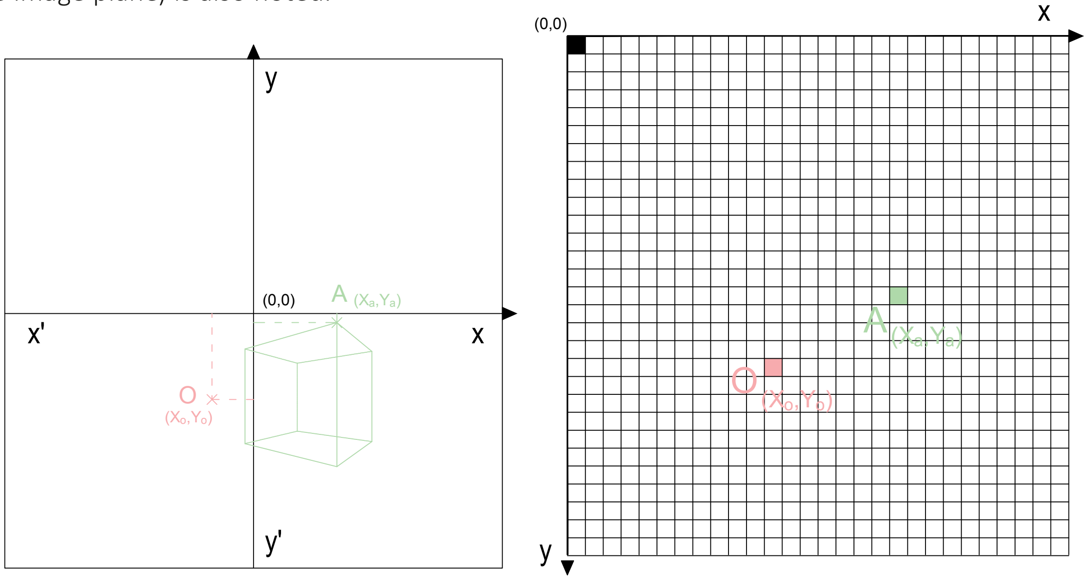
- *the photographic image plane*
- *the camera system (lens-image plane)*
- *& the World (camera-3d object).*

In order to unify them, multiple coordinate systems are employed, one for each "space", which allows accurately description of the involved spatial relationships. When "moving" from system to the next, the coordinates of the various points need to be translated.

COORDINATE SYSTEMS

Image Plane Coordinate System

In order to **extract measurements from an image**, a 2d coordinate system is used: the **image plane coordinate system**. The centre of the axis is usually in the middle of the image. This way, all points depicted have a unique identifier: their coordinates. The **principal point** (projection of the centre of projection on the image plane) is also noted.

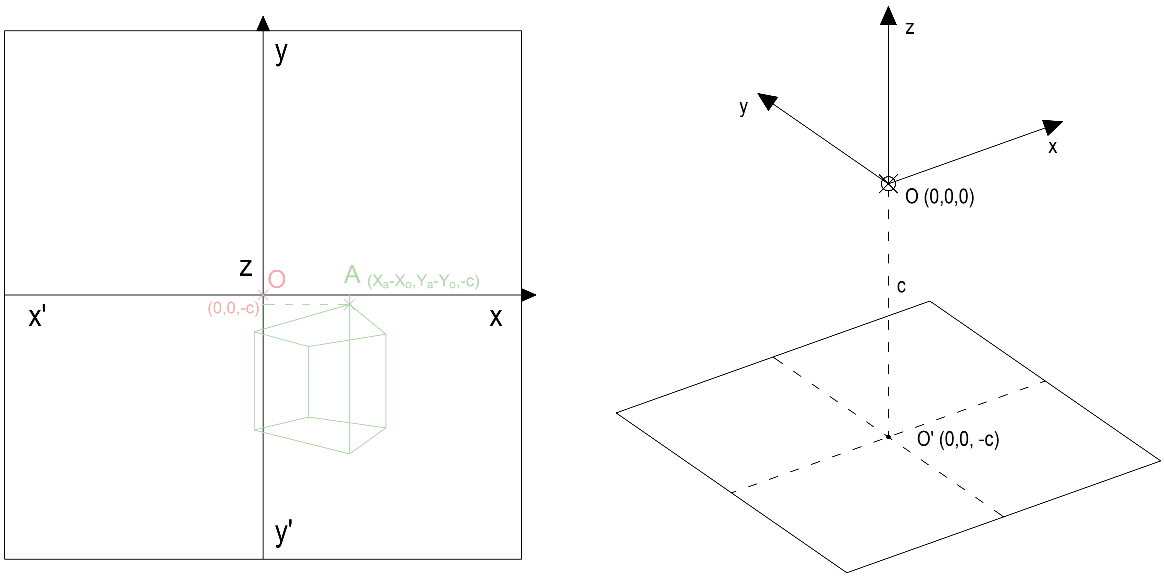


Left: Image plane with its native coordinate system: the centre is in the middle/intersection of the axis. An important element is the location of the principal point, which may but will most likely not coincide with the actual centre of the coordinate system.

Right: Digital image matrix. The centre of the axis is on the upper left corner and the width and height of the image define the size of this plane. Each pixel is identified by its coordinates.

Camera Coordinate System

In order to define **the spatial relationship between the centre of projection and the image plane**, a 3d coordinate system is used, the **camera coordinate system**, as illustrated by the sketch. The centre of the 3-axial system is the centre of projection, whose coordinates therefore are (0,0,0). All image points have a z-value equal to the principal distance, c and their xy-coordinates are recalculated based on the principal point. This coordinate system describes the internal “space” of the image capturing device, the camera.



Left: (New) Coordinates of image point and principal point. Right: Illustration of Camera Coordinate System[1]

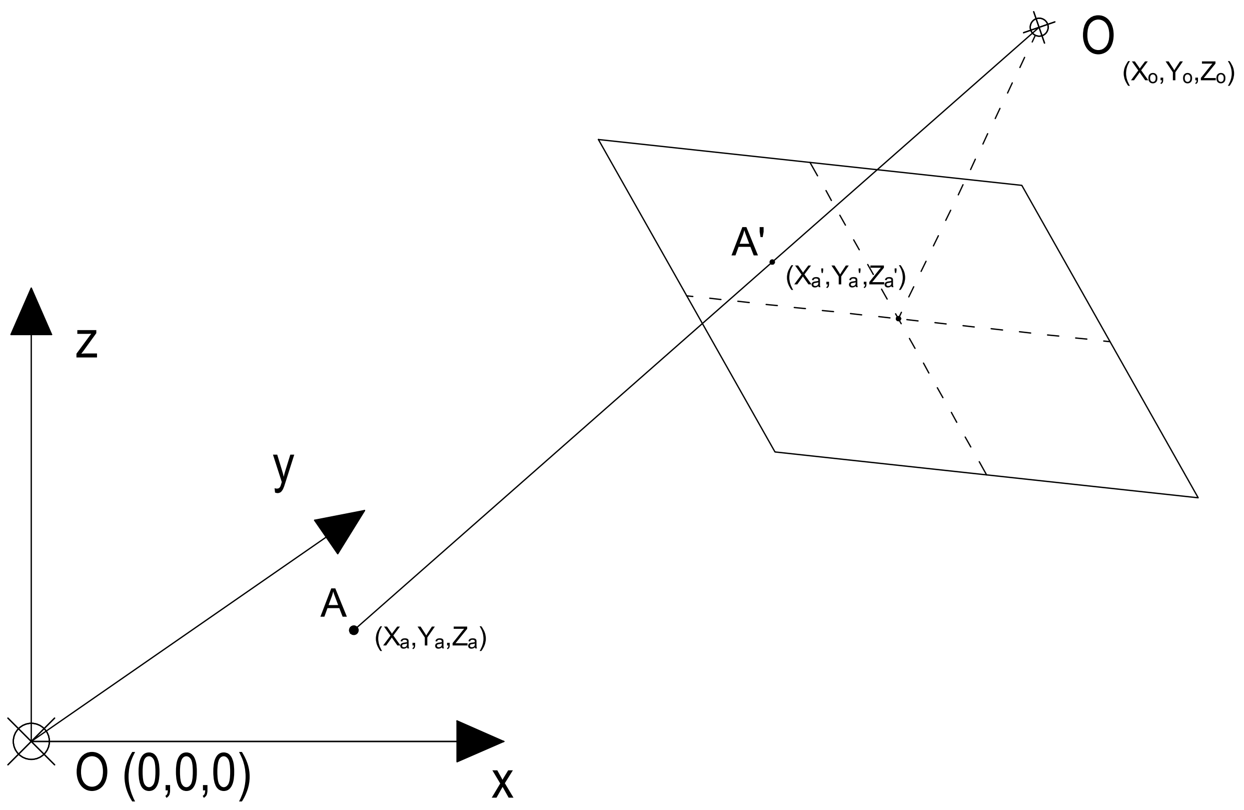
1

After defining the camera coordinate system, the analytical equations that describe each light-ray of the bundle are also possible.

Object/Global Coordinate system

In order to reconstruct the spatial relationship between the **camera & the physical object**, another 3-axis coordinate system is used: the **object coordinate system.** The origin of the axis, this time, is arbitrary and defined by the demands of the occasion. All coordinates measured on the previous system are now translated in the new one.

The “object coordinate system” is in real world units, i.e. metres. The one thing that might vary is its location/definition. It can be the state coordinate system and it can well be a local arbitrary Cartesian coordinate system. This automatically assigns scale to the photogrammetric model.



Degrees of freedom

The degree of freedom is a term that describes the minimum number of coordinates required to specify an element's exact configuration in space. Thus, for photogrammetry, when "importing" an element from a coordinate system into another, the degrees of freedom of the element dictate the amount of parameters/ information that is needed in order to determine its configuration without ambiguity in the new coordinate system. Depending on the element's dimensions, different degrees of freedom occur:

- *Point (0d)* Unknown: Position [3d coordinates] Degrees of freedom: 3 - *Length (1d)* Unknown: Position [3d coordinates, of any point] + Rotation [possible in 2 planes] Degrees of freedom: 5 - *Surface (2d)* - Unknown: Position [3d coordinates, of any point] + Rotation [possible in 3 planes] Degrees of freedom: 6 - *Solid (3d)* - Unknown: Position [3d coordinates, of any point] + Rotation [possible in 3 planes] Degrees of freedom: 6	- *One point* 3DoF (3 coordinates) - *One straight length* 5DoF (3x2coordinates – their length AB) - *Surface (defined by 3 points A, B, C)* 6DoF (3x3 coordinates – 2 lengths (AC, BC) - *3D body (solid)* 6DoF (4x3 coordinates – 3 lengths) - *For each additional point 3 coordinates are added and 3 lengths (to define this point) are subtracted*

Geometric Transformations

In a photogrammetric workflow, geometric transformations of elements are involved. Geometric transformations are functions that transform a set of points from a spatial configuration into another based on a set of rules. Depending on the spatial relationships that are maintained, the transformations are divided into categories. For the interests of photogrammetry, the following transformations are involved:

- *Similarity (rigid-body transformation):*

  A similarity preserves angles, therefore shape (rotations, isotropic scalings, and translations).
  A 2D similarity has 4 degrees of freedom.
  Example: Orienting the image plane with respect to the camera and the world coordinate system.
- *Affinity:*

  A similarity preserves parallelism but not angles.
  A 2D affinity imparts 6 degrees of freedom.
  Example: Removing distortions from photographic image for "true" perspective depiction.
- *Projectivity (homography):*

  A projectivity preserves neither parallelism nor angles.
  A 2D projectivity imparts 8 degrees of freedom.
  Example: Rectification of photographic image/Orthophoto creation.

Surveying Methods

Photogrammetry employs the surveying method of **triangulation** for the restitution of 3d points. Triangulation is the a method for the determination of an unknown position by measuring angles to it from known points, as opposed to measuring distances. Along these angles, rays are drawn, which intersect each other at the unknown point, thus forming a triangle. After the triangulation has been achieved, the unknown points coordinates can be calculated with a combination of known lengths and angles.

In photogrammetry, triangulation is used for the restitution of 3d points.

When determining the position of a 3d point by tracing the homologous light-rays from the known locations of its image points (cameras), the process is termed **intersection**.

When determining the position of the homologous image points(cameras) by tracing light-rays from known 3d points, the process is termed **resection**.

PROCESSES & WORKFLOWS

Now that the concept of multiple coordinate systems has been introduced, photogrammetry's goal can be restated as the **connection between image plane coordinates** & **3d world coordinates**. To perform this task, two types of data input are necessary: **measurements of image coordinates** & **measurements of 3d points**.

Therefore, the scheme of the photogrammetric procedure is as follows:

Input:

- Measurement of image points (2d)
- Measurement & Input of Geometrical Information (3d)

Calculation:

- Reconstruction & Orientation of bundles
- Object Reconstruction by 3d point restitution

3d point restitution

It has been established that **3d point reconstruction** is achieved by **intersection of the homologous rays from the corresponding positioned and oriented bundles**.

Aim:

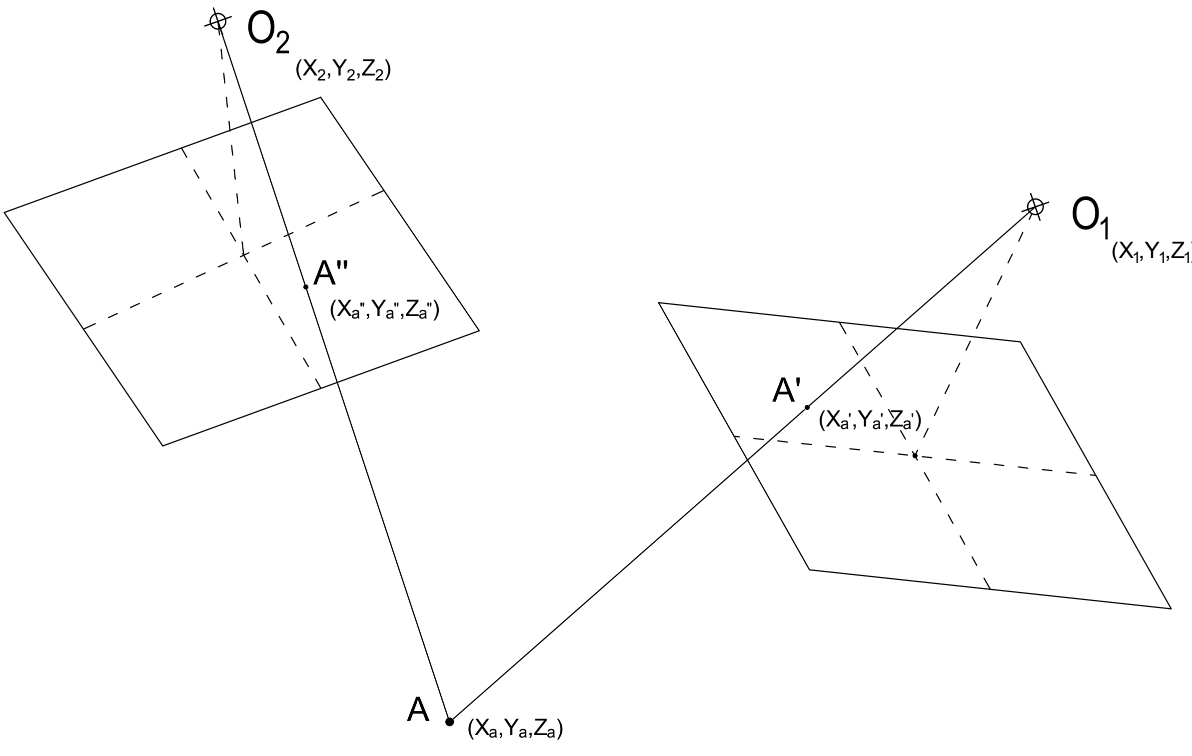
Coordinates of 3d points

Need:

At least two light-rays for each point

Method:

Intersection



3d point restitution by intersection

> Therefore, the main task lies at the **reconstruction & orientation of the bundles**. For this, different methods are available. Three basic workflows are presented:

Workflow a)
1. **Interior Orientation**
2. Image acquisition
3. Measurement & Input of Ground Control points
4. **Exterior Orientation**
5. 3d point Restitution

Workflow b)
1. **Interior Orientation**
2. Image acquisition
3. Input of Tie points
4. **Relative orientation**
5. 3d point restitution
6. Measurement & Input of Ground Control points
7. **Absolute orientation**

Workflow c)
1. **Interior Orientation**
2. Image acquisition
3. Input of Ground control points & Tie points
4. **Bundle adjustment**
5. 3d point restitution

Interior Orientation

The first common step in all workflows is the interior orientation. Interior orientation aims at defining the **internal geometry of the camera**, so that the **central projection model** can be applied for the interpretation of the photograph’s geometry. The main parameter for this is the **location of the projection centre with reference to the image plane**. This is determined by the coordinates of its (vertical) projection on the image plane, i.e. **principal point**, and its offset from the image plane, i.e. **principal distance c**. Additional parameters come into play that remove **distortions** in order to amend for deviations of the photograph from a “true” perspective depiction. Therefore, the **interior orientation parameters** are 4:
- Principal Point coordinates Xo & Yo
- Principal distance c
- Radial distortion values Δr, which actually is described by an odd order polynomial, hence the parameters are the coefficients of this polynomial.
- Tangential distortion, skewness and scale variations between the two axes are further parameters of the interior orientation, albeit of minor importance.

The process to determine the interior orientation parameters is **camera calibration**. After successful camera calibration the **bundle of rays** that originates from the centre of projection point and passes through each image point can be reconstructed.

Aim 1:
Re-establish true central projection from distorted depictions
Need:
Determine internal geometry of camera & lens distortions
Method:
Camera Calibration

Aim 2:
Reconstruct the shape of the light-ray bundle
Need:
Interior orientation parameters

Alternative A) Exterior Orientation

Exterior orientation is the process of **positioning and orienting the bundles in a global coordinate system**. Since the bundle is treated as a rigid body, it has 6 degrees of freedom, therefore 6 unknown parameters need to be calculated (XYZ coordinates and ω,ϕ,κ rotation angles). The positioning of the projection point and the orientation of the optical axis are enough for the determination of the position of the bundle.

This is achieved by **resection** with the help of **Ground Control Points(GCP)**. Ground control points are 3d points that have been **measured** (or have known coordinates) in the chosen global coordinate system. These points need to be **visible** in the image captured by the camera, their location on the image needs to be **identified** and their 3d coordinate need to be provided as input. **Resection** treats the ground control points as the known origin points of light rays that pass from the corresponding image points and end at the projection centre. By resecting light rays from at least 3 Ground Control Points that do not lie on the same line, the **position of the camera can be determined**. This process is repeated for each bundle separately, until all bundles have been positioned. The principle behind this method is the **Collinearity of vectors** from the projection centre to the image point and the 3d point[1].

Aim:

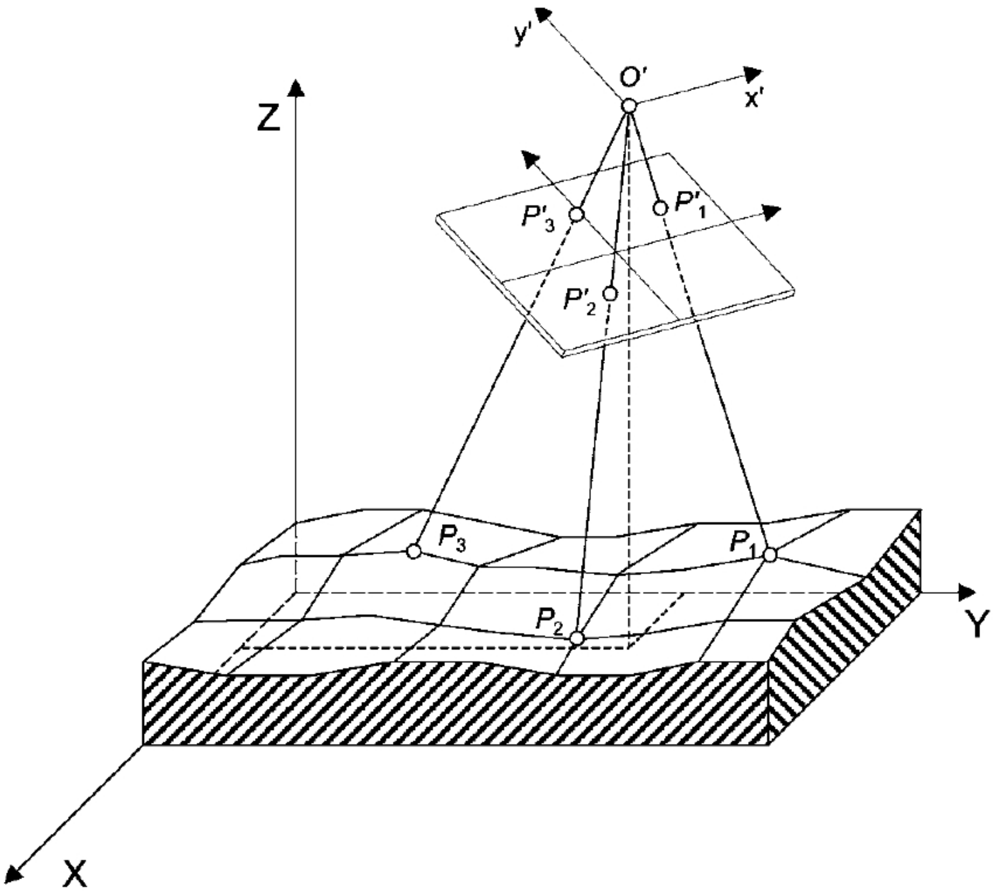
Exact position & orientation of all bundles in space

Need:

At least 3 non-collinear Ground control points visible from each camera.

Method:

Resection



Calculation of projection centre O by resection from GCP P1,P2 and P3.[2]

1 Illustrative explanation of this principle has been given in the central projection chapter.
2 Luhmann, T. et al, “Close Range Photogrammetry”, 2006, Whittles Publishing

Alternative B) Relative & Absolute Orientation

This workflow is divided in two steps: first, in **relative orientation**, each **camera** is positioned **with relation to each other** in a local coordinate system (without the need of GCPs, and therefore, without scale) and afterwards, in **absolute orientation**, the whole "rigid body" of **bundle-configuration** -along with the **reconstructed object**- is placed in the global coordinate system in its true scale and location. This method is commonly used in **stereophotogrammetric** workflows, where the **spatial relation of the image pair** is very important, since it allows (or denies) **stereoscopic viewing** of the images.

For the relative orientation of cameras, **tie points** are used as geometric reference instead of GCPs. Tie points are **homologous image points** (i.e. images of the same 3d point) which have been identified across photographs. The accuracy of the orientation depends on the amount and distribution of the tie points on the images.

Relative

Aim:

Reconstruction of spatial relationship between a pair of bundles / images,

Need:

At least 5 tie points for the positioning of two paired cameras

Absolute

Aim:

Definition of the previously reconstructed object's exact spatial configuration (location, orientation & size)

Need:

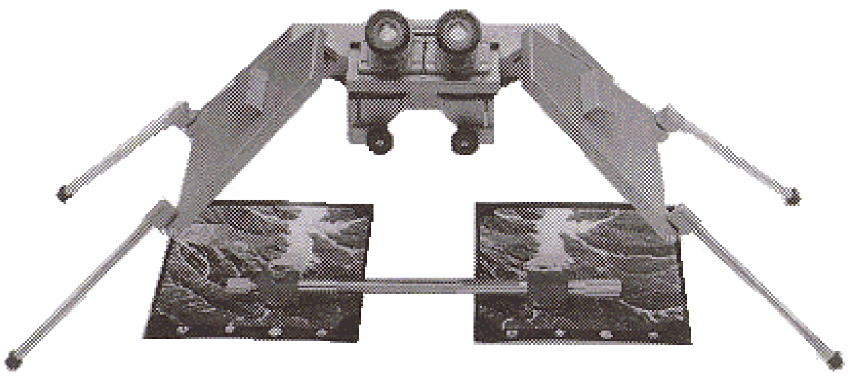
Ground Control Points (2 (X, Y, Z) and 1 (Z))

Method:

Manual Input of GCP coordinates

**Stereoscopic viewing*

Stereoscopic viewing is achieved when images in approximately **same scale** (from same shooting distance/**base**) have almost **parallel optical axes** to each other and enough **overlap** to offer **binocular disparities** and trigger human **depth perception**[1]. The images need to be in such a spatial configuration to each other, so that **y-parallax** is **eliminated** (or equivalently the homologue ray pairs intersect) and the **x-parallax** can be used to calculate the **depth value** of the target point.



Stereoscopic viewer of prepared images[2]

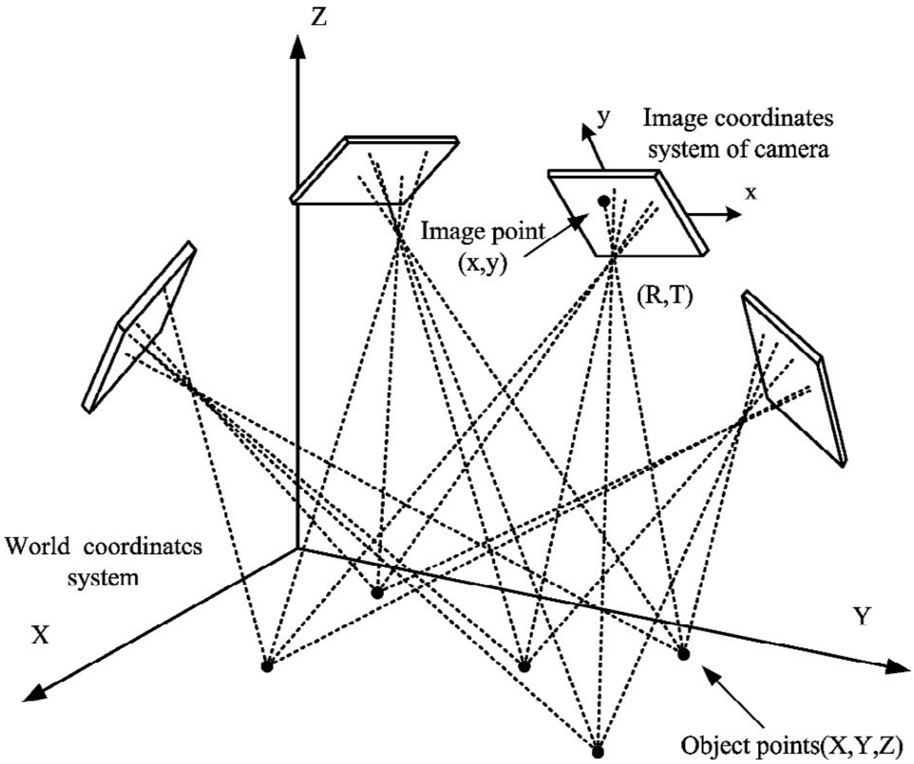
1 For detailed information on this, please see corresponding chapter in the appendix section.

2 http://wtlab.iis.u-tokyo.ac.jp/~wataru/lecture/rsgis/rsnote/cp7/cp7-3.htm

Bundle adjustment

Bundle adjustment is an **iterative** approach that calculates **all parameters of interior (if wished) and exterior orientation simultaneously**. Some initial values are used and with every iteration the values are recalculated until an optimal configuration has been achieved. Bundle adjustment needs input of both **tie points** and **ground control points**. The coordinates of GCPs can be in the object coordinate system, leading to a model of unknown scale or in a global coordinate system, thus achieving georeferencing and scale calculation also.

*Although calculation of interior orientation parameters is simultaneously included in bundle adjustment, **camera calibration** before the bundle adjustment, will provide a benefit in terms of accuracy.



Bundle adjustment[1]

1 http://opticalengineering.spiedigitallibrary.org/article.aspx?articleid=1183301

CAMERA CALIBRATION

Camera Calibration is the procedure by which the **interior orientation parameters** of the camera are estimated. The geometric model used for the camera in photogrammetry, as explained, is the pinhole camera model. The interior orientation parameters define the **particular central projection model that best describes the camera.**

By establishing the **principal point coordinates xo & yo and the principal point distance c**, the internal geometry is defined. Nonetheless, actual photographs are observed to have significant differences from true perspective images. These differences are due to various reasons, for example:

- Physical lenses cannot be identified with the “thin lens” model, namely with a point of negligible dimensions.
- Lenses by nature infer aberrations on the projected image.
- Lenses may suffer from manufacturing flaws.
- The image sensor surface may be neither planar nor perpendicular to the optical axis of the system.

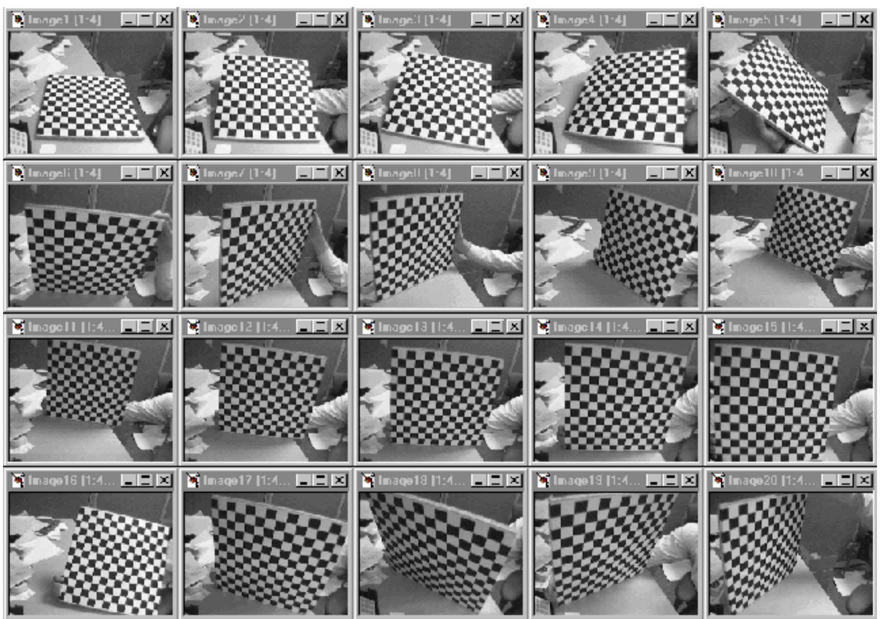
Therefore, more parameters come into play, most notably the **radial and tangential distortion parameters**. In order for central projection to be adopted as an accurate model for the photographic depiction process, amendments for these distortions need to be made and it is obvious that in theory, if the distortion parameters of the central projection are known, regardless of the degree of distortions imposed, corrections can be applied & accurate measurements can be made.

Summary

Camera calibration is necessary because of the **differences between an image composed by the abstract model of central projection and an image composed by an actual, physical photographic apparatus**.

Camera Calibration Method

There are **various methods** for calculating the interior orientation parameters of a camera model. The common concept is the **comparison between the depicted geometry and the physical object/reference**, which is of known geometry. Out of this comparison process, the parameters are calculated. The calibration methods can be categorised based on the geometrical dimensions of the reference object.



Camera calibration in Matlab using chessboard target[1]

1 http://www.vision.caltech.edu/bouguetj/calib_doc/htmls/example.html

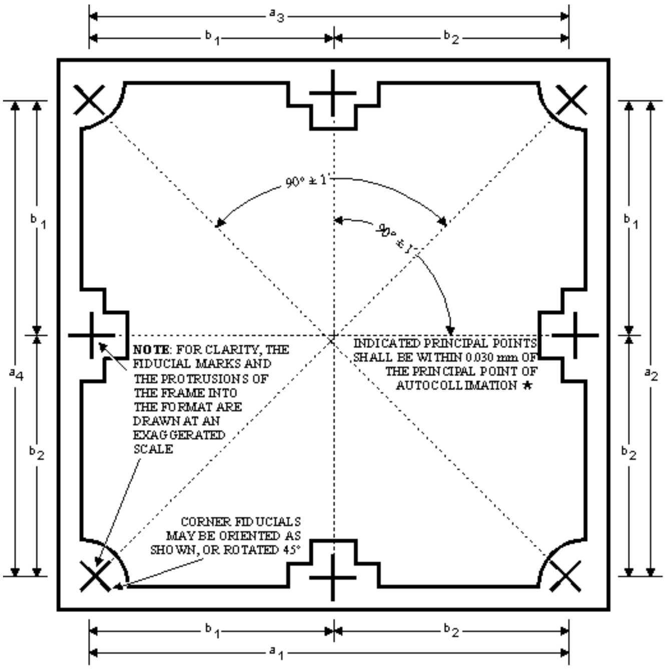
THE PHOTOGRAMMETRIC CAMERA

> From Professional Metric Cameras . . .

From birth and during the analogue and analytical era of photogrammetry, special cameras were developed specifically for facilitating metric information extraction, the so-called metric cameras. Their main characteristics are the following:

- **Known interior geometry** / parameters of interior orientation
    - principal distance
    - principal point position
- **Stable interior geometry**
- **Fixed lens systems** = fixed focusing distance
- **Low lens distortions**, especially radial distortions
- **Fiducial marks**[1] projected on images, to define a reference system for image coordinate measurements
- Possibly, a **reseau**, an array of engraved crosses, projected on each image.
- *** Analogue Film flattening devices** (mechanical, pneumatic etc.)

Metric camera manufacturers provided their instruments with a calibration certificate, which describes in detail the camera's geometry. The cameras are pre-calibrated at specific, **fixed focusing stops**, for example at **close range & infinity focus**.



Fiducial Marks[2]

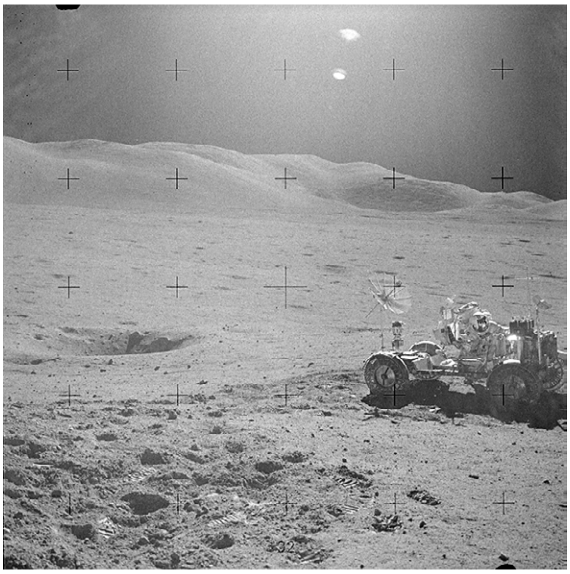


Image with Réseau plate[3]

> To Consumer DSRLs

Non-metric cameras were also used for photogrammetric purposes, mainly for their versatility, low weight, interchangeable lenses and, of course, low cost. Initially they were seen as angle recording instruments of lower accuracy, suitable for less demanding applications.

Nowadays though, consumer cameras have a high technical standard and enough imaging resolution to render them suitable for close-range photogrammetry, while still being affordable for small/lean-budget projects or by non-professionals. Furthermore, the advancement of computer power, the refinement of photogrammetric algorithms and the development of software to perform self-calibration, has lead to non-metric cameras becoming **the norm for terrestrial applications**.

1 Fiducial Marks at first used to were 4 either positioned in the corners or the middle of the image edges, later metric cameras have a combination of both resulting in 8 marks
2 http://calval.cr.usgs.gov/osl/fig2.html
3 http://www.aulis.com/composites.htm

SINGLE IMAGE PHOTOGRAMMETRY

It should be noted that photogrammetry can in specific cases yield information about an object by a single photograph, as long as some conditions apply.

2D

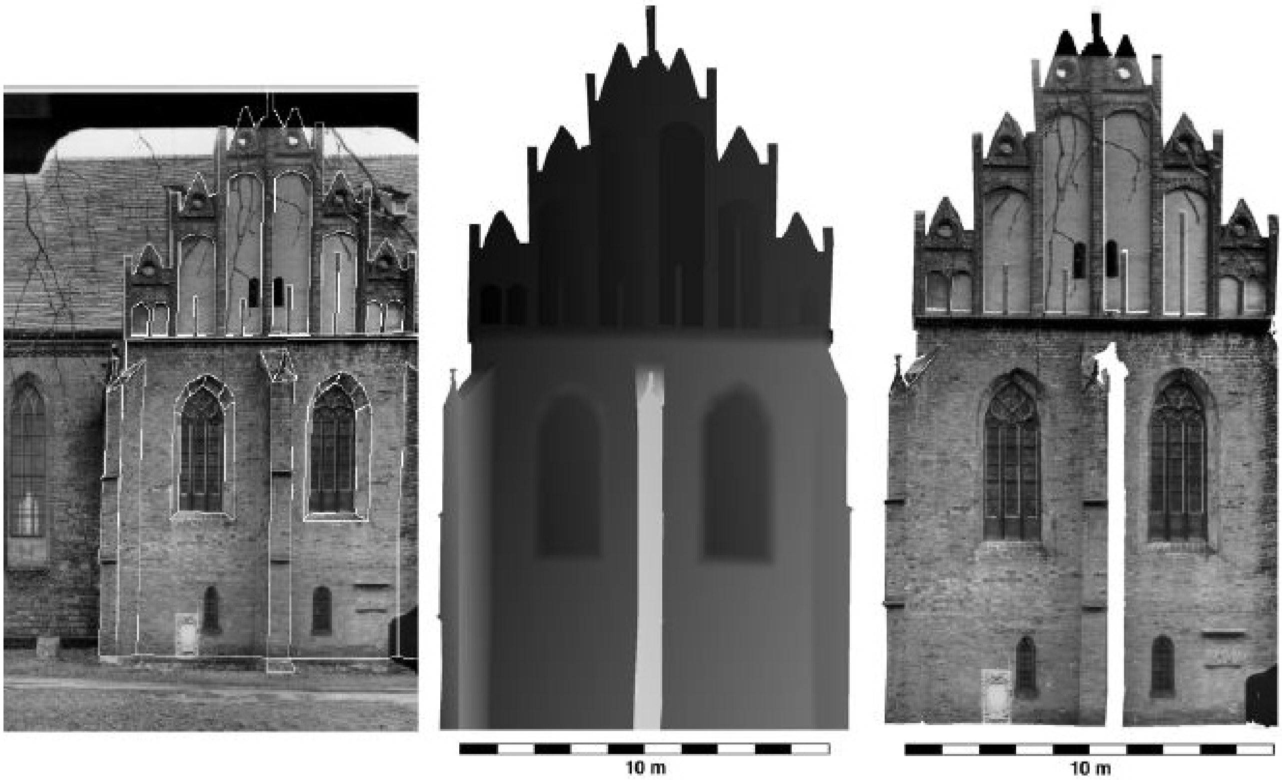
The object in question is a **planar surface** or **object with negligibly small relief** that can be treated as such.

In this case, a transformation of the photographic image from **central projection** to **orthographic projection** is adequate to make reliable measurements about the object.

This is a projective transformation that has 8 degrees of freedom, therefore 4 points with known measurements from the physical object are enough, since every 2d point yields 2 parameters (XY coordinates).

The process of transformation from a central projection to orthographic projection is called **image rectification** and the resulting image is termed **orthophoto** and is a valid metric reference.

It should be noted that given a photographic image and its corresponding depth map, any photo can be rectified into an orthophoto[1].



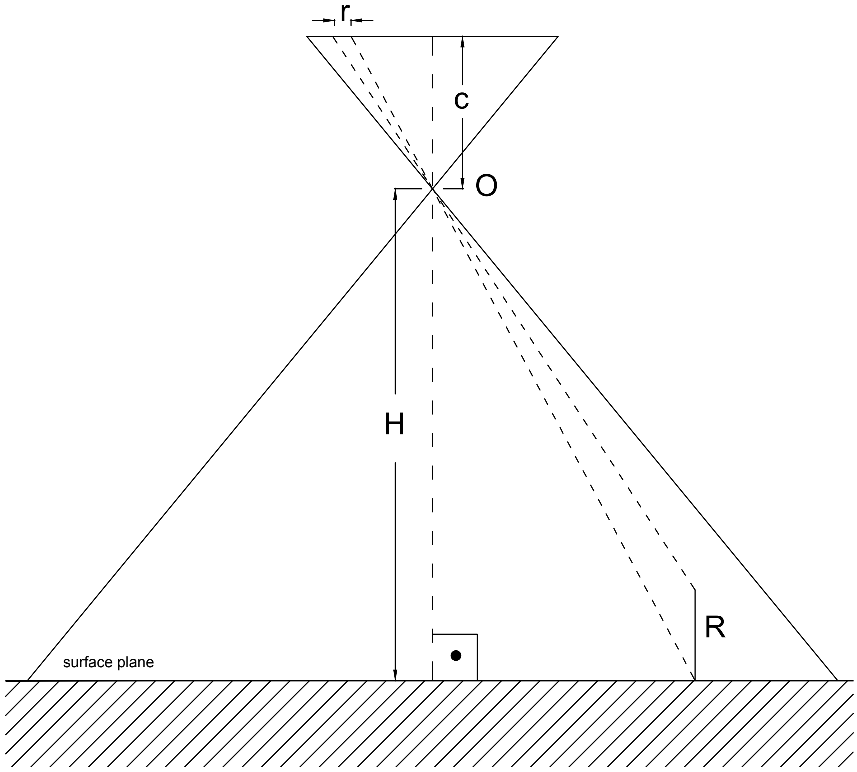
Photograph(with vectorized 3d data), Depth Map and generated Orthophoto[2]

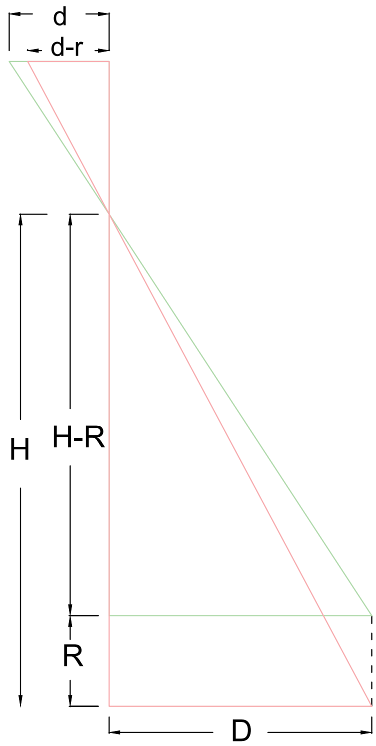
1 Despite this, photographs at oblique angles that have a large point scale variation will lack necessary colour information to construct an orthophoto.
2 Luhmann, T. et al, “Close Range Photogrammetry”, 2006, Whittles Publishing

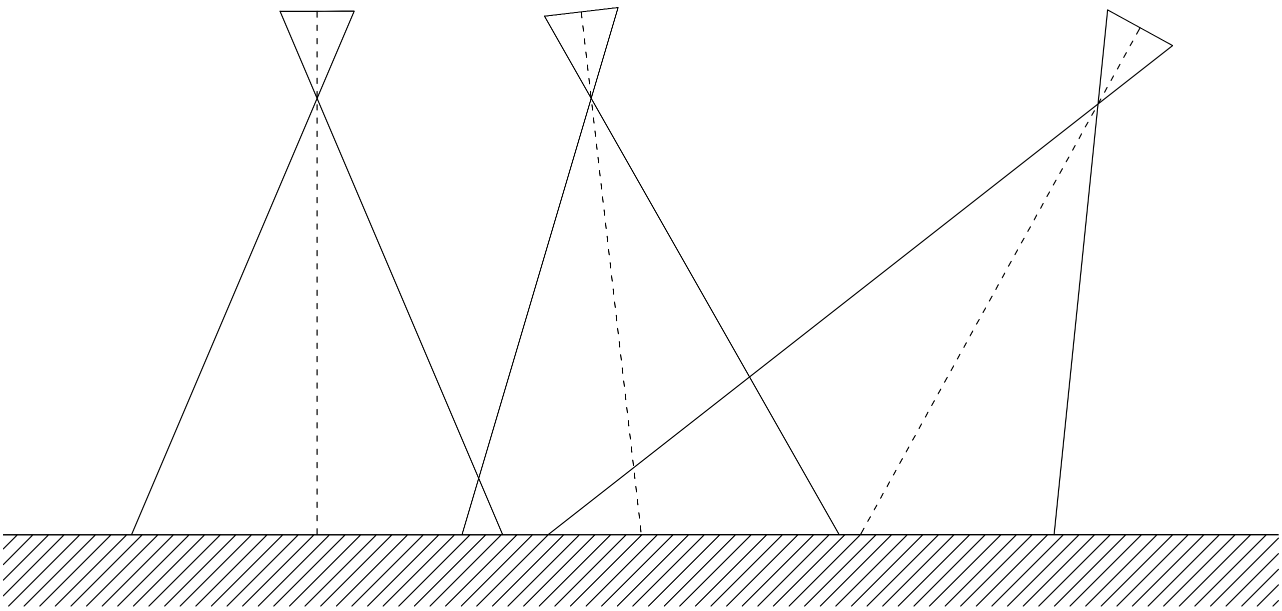
2.5D

In **purely vertical shots**, the theorem of similar triangles can be applied. Thus, knowing the principle distance c and the shooting distance from the surface plane, H, the vertical length R can be calculated by measurements on the image. The geometrical sketch on the right illustrates the method.

The shift of the end vertex of R due to its elevation from the surface plane is termed **relief displacement**.







Orientation of Optical Axis with reference to (approximate) surface plane: Vertical shot, nearly vertical and oblique shot. Similar triangles are not formed in oblique shots and the point scale in the image varies greatly.

DIGITAL PHOTOGRAMMETRY & COMPUTER VISION

Computing in un-human speed

Contemporary digital photogrammetry can be introduced as a specific field of **computer vision** and its main characteristic is the employment of **digital image analysis** for the automated recognition of tie points between sets of images. Photogrammetric tie points in computer vision terms are called **feature matches** and their **automated extraction** greatly facilitates both the **bundle adjustment stage** as well as the **3d point reconstruction**. Manual user input is minimized and point cloud of considerable sizes can be computed. Iterative bundle adjustment (with or without GCPs) is the standard procedure in an automated digital photogrammetry. Optimization techniques are employed for higher accuracy results.

In computer vision terms, automated photogrammetric workflows are described as **Structure-From-Motion (SFM) - Multi-View Stereo(MVS)** workflows. **SfM** is the process which includes extraction of homologue points on neighbouring images and establishing the spatial relationship of the image bundles (relative orientation). **MVS** is the next step in which a great number of 3D points are extracted (and their surface reconstructed) from the relatively oriented images in the previous step.

A significant amount of **open source software** or **toolboxes** on these subjects are available and under development, making the Sfm-MVS workflow particularly open to a wide audience.

Structure from motion

As the name implies, Structure from Motion denotes the **estimating of 3D geometry** (**structure**) based on **different camera positions** (**motion**). For this to be achieved, corresponding points between image pairs need to be located. This task is termed as the **Correspondence Problem**.

Procedure Overview

Step 1) Image analysis - implementation of interest point operators

Feature extraction:

The goal at this step is to locate and describe specific points on each image.

Feature Matching/Correspondence problem:

Points from all images are compared to each other, with the aim to find corresponding image parts.

Tie Point/Sparse Point Cloud

The output of this step is called a sparse point cloud, consisting of the 3D coordinates of those points that were used to align the images.

Step 2) Bundle Adjustment & 3d Point Restitution

Dense Point Cloud

In the next step, a high density point cloud, termed dense cloud is created that is a very close representation of the real physical objects in the photographs.

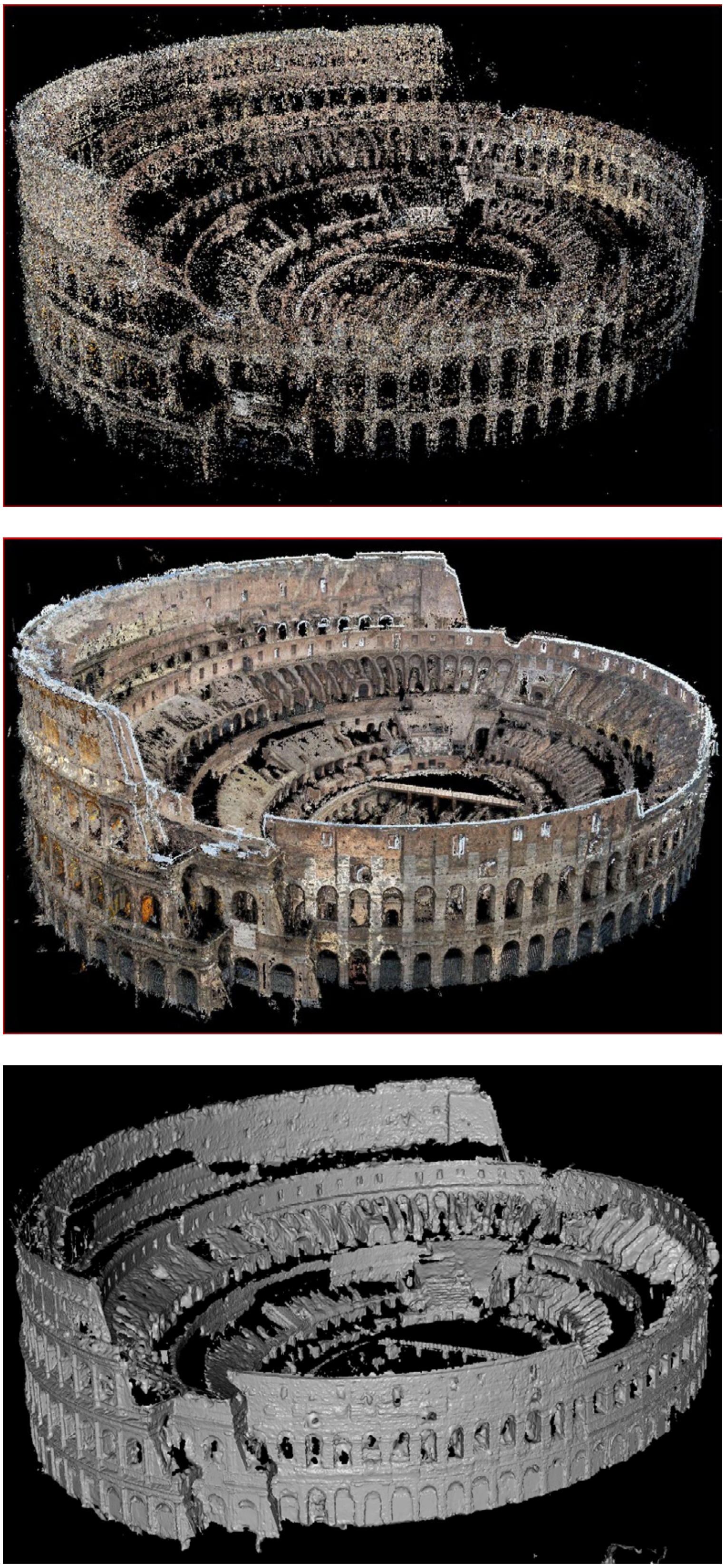
Step 3) Mesh Generation

This cloud can then be turned into a polygon mesh which consists of triangles that connect the points.

Step 4) Texture Generation

Colour information can be included by directly taking the colour of the various points from the photographs or by separately calculating a texture for the mesh.

Building Rome in a day project



Photographic input from unordered internet-sourced image collection
Sparse point cloud from Sfm
Dense Point Cloud from MVS
Mesh by triangulation of the dense point cloud[1]

1 https://grail.cs.washington.edu/rome/

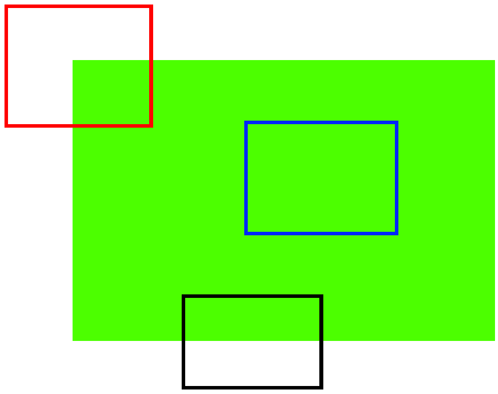
Image Analysis

Correspondence problem

The correspondence problem deals with finding **corresponding parts between pairs of images**, which **depict the same scene taking from different angles**. After completion, a fundamental matrix[1] is created that describes how the image parts are related. A common algorithm for this process is the RANSAC algorithm. A typical application of the correspondence problem occurs in panorama creation or image stitching, i.e. when two or more images which only have a small overlap need to be stitched into a larger composite image. The correspondence problem is resolved by image analysis, the first step of which is **feature detection**.

What is an Image Feature

In computer vision terms, **image features** are the means by which an image can be "read" and described. Features consist of specific patterns or elements which are unique, and can therefore be easily tracked and compared.



Windows over corner, edge and surface areas of a shape[2]

Feature Detection

The most easily describable areas of an image are areas with **maximum variations in their surroundings**: this plurality of relations makes them easily recognisable. Therefore, it follows that corners are more suitable than edges, which in turn are more suitable than flat surfaces. Feature Detection algorithms "search" images for regions which have this property of maximum variation in the surrounding neighbourhood by using a "search window" which scans the image matrix. Thus, image feature are identified.

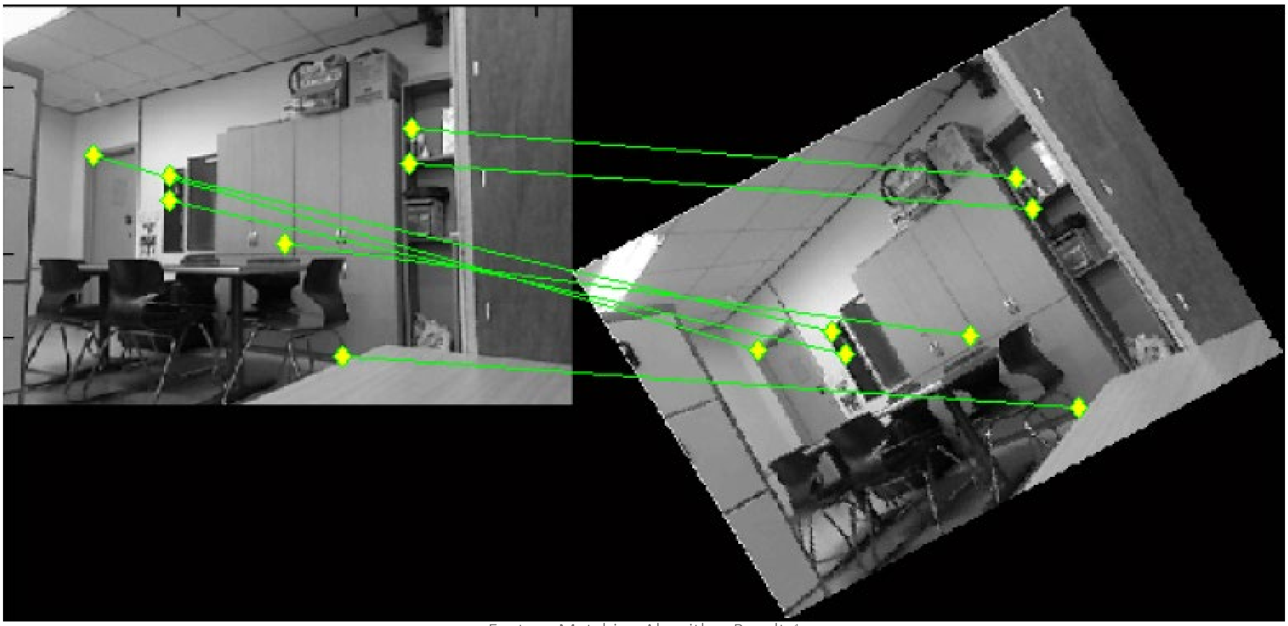
Feature Description

Features are recorded by their **location on the image matrix** and **described by their relations to neighbouring pixels**. Comparing these relations/neighbourhoods allow the feature matching algorithms to identify the same feature across images.

Feature matching

Feature matching algorithms use the **descriptors of a feature** in the first image and compare them with all other features in other image. The comparison results are recorded using some **distance calculation** and the **closest match** is returned.

1 https://en.wikipedia.org/wiki/Fundamental_matrix_%28computer_vision%29
2 httpdocs.opencv.orgmasterdbd27tutorial_py_table_of_contents_feature2d.html#gsc.tab=0

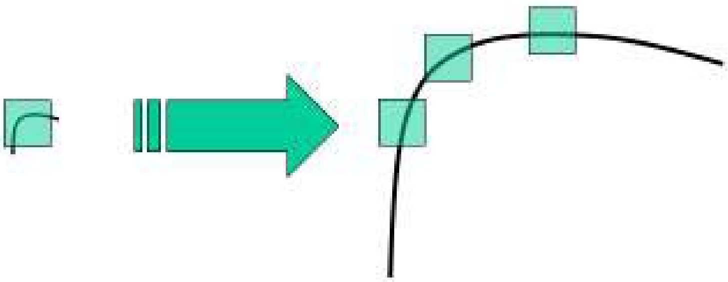


Feature Matching Algorithm Results[1]

> Scale Invariant Feature Matching/SIFT algorithm[2]

When the same feature is rendered in different sizes (whether due to photographic scale or image resolution), its detection will vary, since its size to the "reading" window of the feature detection algorithm changes. This means that the same feature cannot be easily matched across different images.

In order to overcome this obstacle, the scale invariant feature matching algorithm was developed, also known as SIFT algorithm[3]. SIFT is a well known interest point operator.



Shape Scale to "window" size[4]

1 http://opticalengineering.spiedigitallibrary.org/article.aspx?articleid=1373414
2 http://docs.opencv.org/master/da/df5/tutorial_py_sift_intro.html#gsc.tab=0
3 Developed in 2004, by D.Lowe (University of British Columbia) and presented in his paper "Distinctive Image Features from Scale-Invariant Keypoints".
4 httpdocs.opencv.orgmasterdbd27tutorial_py_table_of_contents_feature2d.html#gsc.tab=0

DIGITAL REPRESENTATION & EDITING OF 3D GEOMETRY

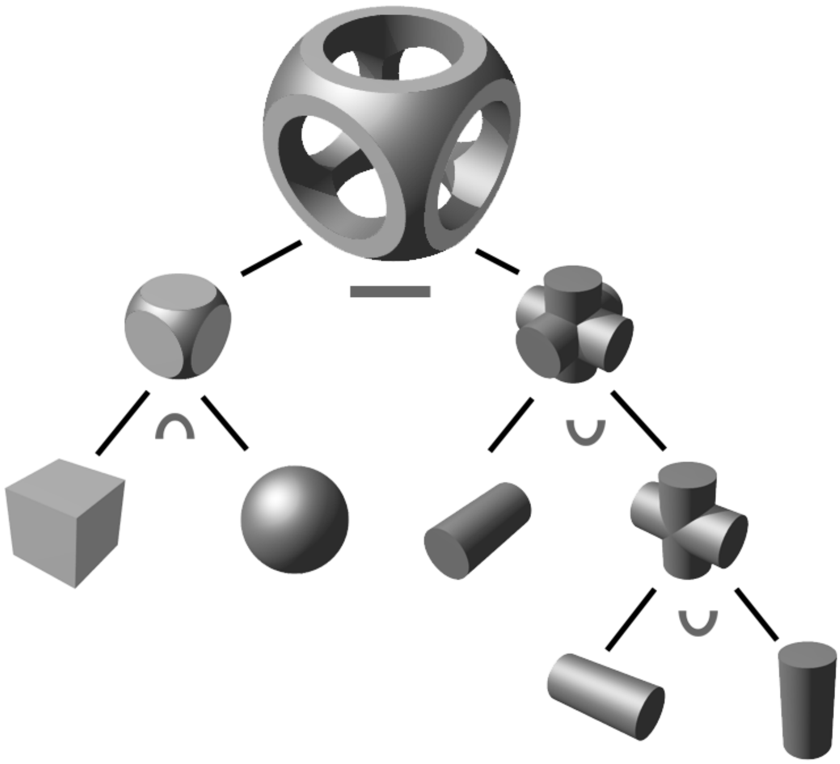
Given the fact that a digital photogrammetric project will -among others- result in a 3d geometrical file, it is useful for the user to acquire some theoretical understanding on the subject of digital 3d modeling. Different 3d “management” approaches exist, a first-level distinction can be between 2 types:

- *Parametric definition,*

where geometrical entities are described by **mathematical equations & logical operators**.

Under this approach, the **object-instances**, derived from the available **object-entities**, are described by means of **parameters**, to which the user can attribute **values** at object creation stage or even dynamically.
**An example on this line of thought is NURBS[1] modeling, which supports high accuracy, mathematically defined/formula-driven creation of curves.*

Parametric definition of objects allows for procedural modelling, such as in the modelling approach of **Constructive Solid Geometry** (CSG), where the final form is derived by performing **boolean operators** (such as intersection, difference, union) on a range of available **primitive solids**.

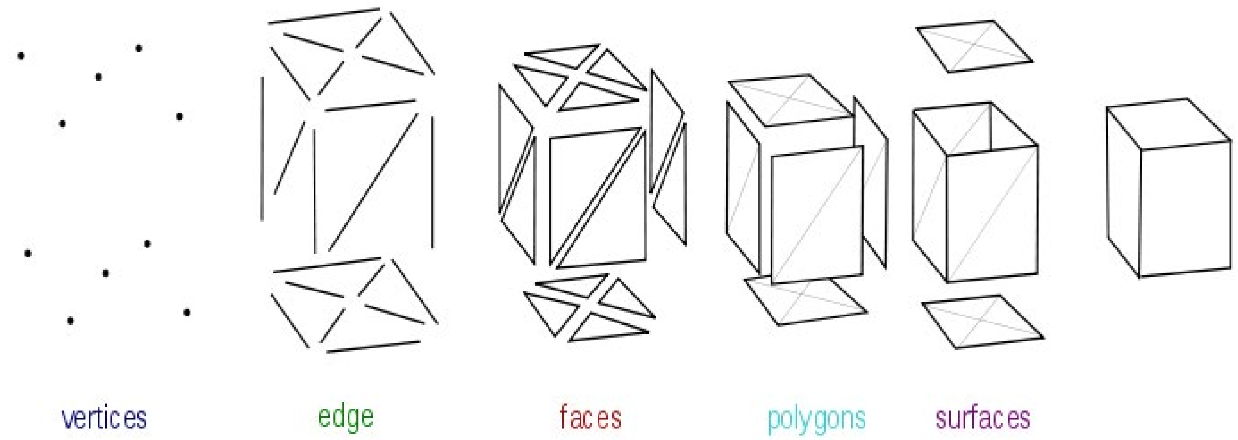


Boolean operators on primitive solids[2]

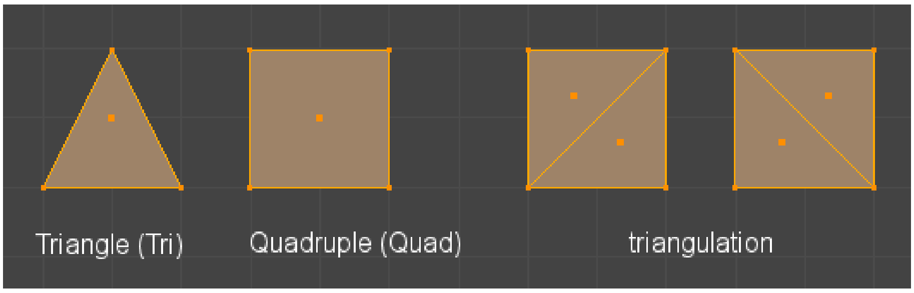
- *Geometric definition,*

where no mathematical/logical description of the form exists, but rather, **a listing of structural elements**. These elements usually consist of **3d points**, which act as **vertices** to define **line segments**. These, in turn, define **polygons**, which describe the external **boundaries**/shape of the object. There is no concept of “volume”, only **orientated surfaces**(two-sided), that define the object’s **shell**. The structural units, the **polygons,** are in **triangular** or in **rectangular** formation, known as **tris** & **quads**[3]. The characteristic trait of this non-parametric approach is its non-responsiveness.

1 Non-uniform rational basis spline.
2 https://en.wikipedia.org/wiki/Constructive_solid_geometry
3 Quads in essence are comprised of triangular surface units. They are oftenly rendered as such, since quad tesselation is the basis for Subdivision Surface Mesh modeling, which is a very important 3d modeling process. Also, the fact that quads break down cleanly to 2 or 4 triangles offers interoperability between 3d editing software that handles only triangulated meshes.



Structural elements of polygonal modelling



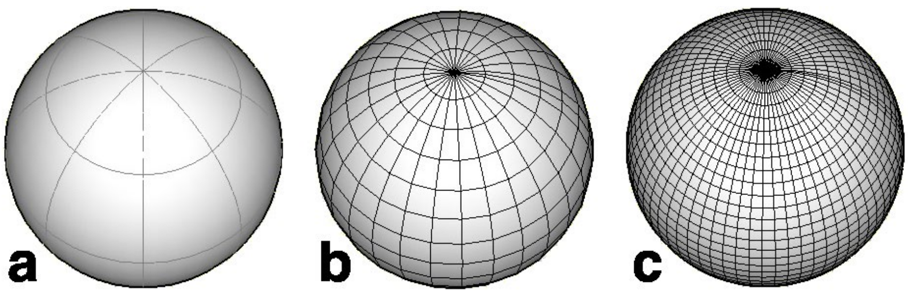
Triangle (Tris) & Rectangle (Quads)Units [1]

> The meshes generated from the point clouds of the photogrammetric process fall in the geometric modeling category.

- *Polygonal Modelling*

Creating models with polygonal meshes is known as **Polygonal Modelling**. Nowadays, there is a “split“ in the established polygonal modelling workflow, aptly called the split between “**additive**” and “**subtractive**” modelling. The goal (in terms of desired properties for the final model) is common in both workflows but the methods to achieve them differ.

The qualitative measure of a polygonal model is primarily the balance between **mesh size** and achieved **level of detail** and secondarily, the shapes and placement/relations of the polygons themselves, its **topology**.



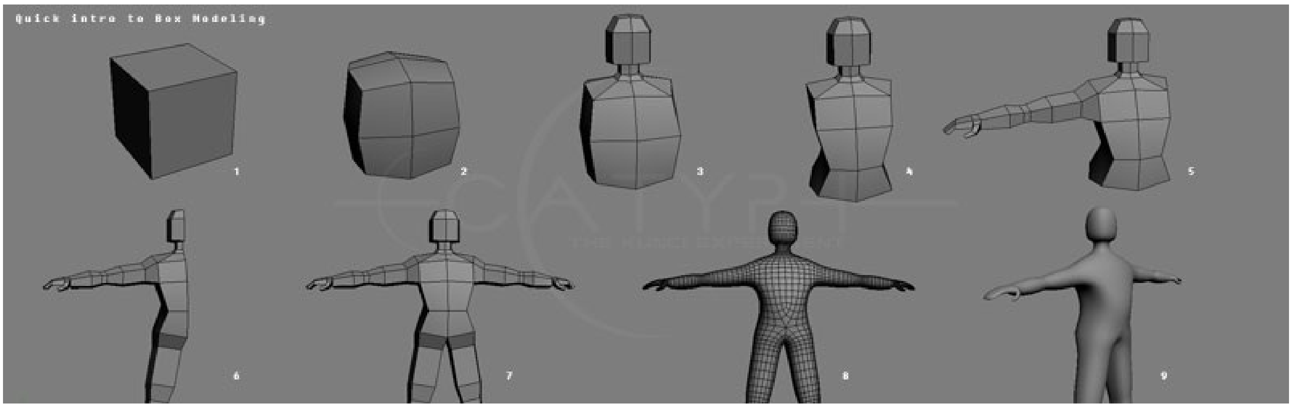
From a to c: increasing mesh resolution/size[2]`

1 http://blog.machinimatrix.org/wp-content/uploads/2011/09/tut_2252.png
2 http://www.formz.com/manuals/formz7/!SSL!/WebHelp/10810_Polygon_Mesh.html

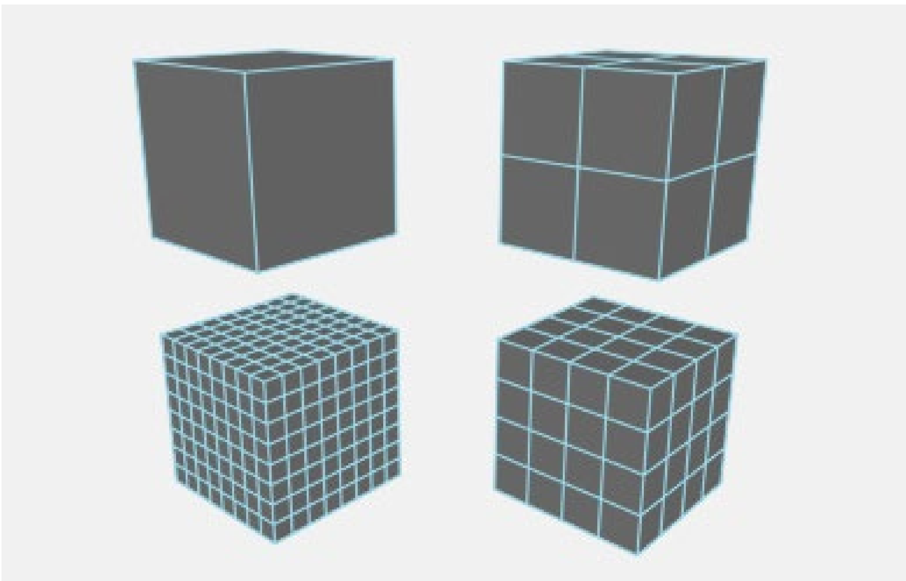
I. The additive method

Box modelling

Up to now, the most typically used method, taught as the “traditional” 3d modelling technique for polygonal organic modelling, was **Box modelling**. Box modelling starts with basic geometric entities/objects of a “primitive” shape[1] (not necessarily a box) that can be further refined and/or combined by a means of various operations, most notably, by adding edges. This method can also be termed as “**additive**”, since in order to refine a shape to the desired complexity, new polygons are added by subdividing the existing ones, and thus enlarging the mesh size. The process of generating new polygons by splitting existing ones is termed **Subdivision Surface modelling**. For the implementation of this technique, quads are the optimal basic polygonal unit for the mesh, since quads can ensure stability in the up-downscaling of the optical resolution of the model. At each step, the density of the model is in/decreased systematically, since each face is multiplied/divided by a factor of 4. When the desired level of detail has been achieved, the mesh size is regarded as having reached optimum size and the modelling procedure is complete.



Box modelling example[2]



Quads are ideal polygonal units for mesh Subdivision[3]

1 Typically a cube but in many cases can be any of the following: Pyramid / Cylinder / Torus / Cone / Sphere
2 www.hiveworkshop.com
3 http://i0.wp.com/blog.digitaltutors.com/wp-content/uploads/2013/11/Subdivide1.jpg

II. The subtractive method

Voxel [1] Sculpting

In contrast, the next-generation approach -**Digital/Voxel Sculpting-** can be termed as "**subtractive**", since modelling procedure continues until a very finely detailed high-polygon mesh is generated, which later on needs to be decimated, in order to render it practical and lightweight.

In digital sculpting, modelling is more intuitive and could be seen as the digital version of hand-working with clay, since it employs tools such as push/pull/pinch/smooth. Working, at first, with no regard for model efficiency helps to increase expression and artistic creation. Afterwards, skills in **geometry optimization** and **retopology** are necessary to create an "affordable" low-poly version of the mesh, while maintaining **geometry fidelity** of the original model.

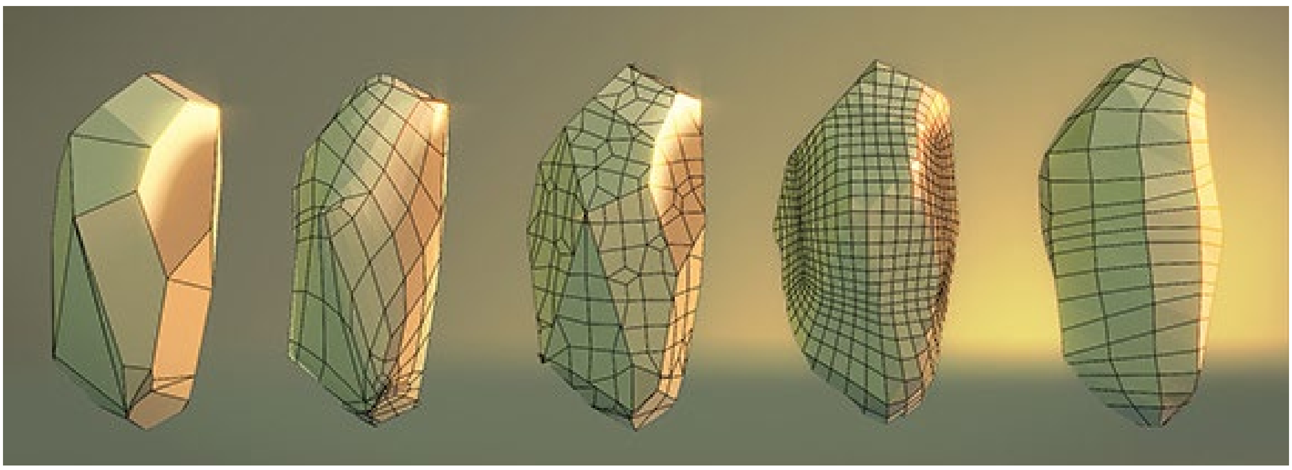
The process therefore is as such:
- *Sculpting*
- *Retopology*
- *Derive UV Map*
- *Up-Res of Model*
- *Sculpting to fine Detail*
- *Derive Normal Map*
- *Derive Displacement Map*
- *Switching to down-res mesh*
- *Apply Maps*
- *Render*

Popular digital sculpture applications include Pixologic's ''Z-Brush'' and Autodesk's ''Mudbox''.

Retopology

Retopology is the process of **simplification of the mesh description** of an object with the condition of **preserving unaltered its geometry**. This yields more efficient models as input for later stages of the work-flow. The process involves taking a high-density mesh and tracing it with new polygons in order to reconstruct the original using less dense, more efficient spatial relationships. The goal is not only to create an **efficient, lower-density mesh** but also with accurate and systematically contrived **edge placement**.

Current software that deal with retopology issues include packages such as ''Topogun'', Autodesk's "Maya" or ''3D-Coat.'' Automatic retopology tools can optimize the retopology process, for example by dealing only with equal-sized triangles and quadrangles (ideal surface tessellation) or by paying attention to edge flow.



Retopology considers polygon count and edge flow[2]

1 Voxel is a portmanteau of "volume" & "element", as "pixel" is for "picture" & "element"
2 http://blenderartists.org/forum/showthread.php?322607-Blender-Quick-tip-%26%238470%3B6-Retopology-creating-stones-pt-2

3d Modelling Basic Terminology

Wireframe 3d model of Utah Teapot[1]

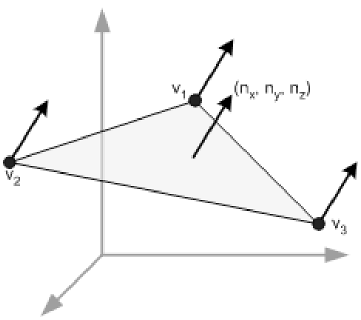
Summary

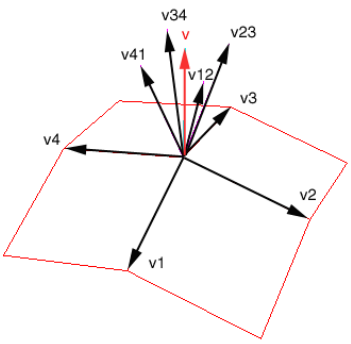
Up to now it has been explained how 3d geometry is represented in a polygonal modelling software environment: the elementary unit is the 3d point (treated as a vector). Points are interconnected with line segments, creating a triangular network. Since multiple triangles may be connected to form polygons, the surface created is termed as polygonal mesh. This surface needs to be oriented, since it acts as a boundary, thus one side needs to be termed as outward and one as inward.

"Normal" Vector

For the purpose of surface orientation, **normal vectors** are used. In 3D computer graphics, the term ''**normal**'' refers to an **imaginary vector** that is **perpendicular** to each triangle/polygonal surface. The direction of the normal vector points to the outward side of the polygon. The term "normal" denotes the normalization process of the vector, i.e. the fact that normal vectors are of unit length and only their orientation information (rotation in space) is of interest.

The direction of these normal vectors are compared to the vector of the line of sight of a camera or a light. The resulting viewing angle (or ''**facing ratio**'') can be used to calculate any number of **dynamic visual effects**, such as reflected illumination (Lambertian diffuse illumination model).





Left Image: The normal vector of the polygon is perpendicular to its plane and defines the normal vectors of its vertices[2].

Right Image: The vertex normal of the vertex is a combination of the normal vectors of its adjacent polygons.[3]

1 http://www.renderspirit.com/wireframe-render-tutorial/
2 http://www.songho.ca/opengl/gl_normaltransform.html
3 http://www.lighthouse3d.com/opengl/terrain/index.php?normals

Visual Appearance

After establishing the geometrical information of the model, input of its colour information comes next. In physical world, the **visual appearance** of an object is determined by the combined effect of a variety of factors, most notably of two types: **environmental factors** (such as scene luminance, viewing angle and distance, atmosphere, sensor sensitivity, etc.) & the **visual attributes of the object** (such as colour, reflectivity, transparency, relief, etc.) This effect needs to be simulated in the digital environment by the interaction of the model and the camera via the rendering engine. For this task, modelling software programmers have defined/coined a list of visual attributes which can be assigned with values to describe the "physical" appearance of a model, if rendered in a photorealistic way. It follows, that rendering engines have been programmed to compute the visual outcome based on the interconnections of these properties with each other and the camera. These properties are based on working theories/assumptions, and as a result, specific terminology and mechanisms may vary from software to software, but most properties, though, have been standardized by practice.

Texture

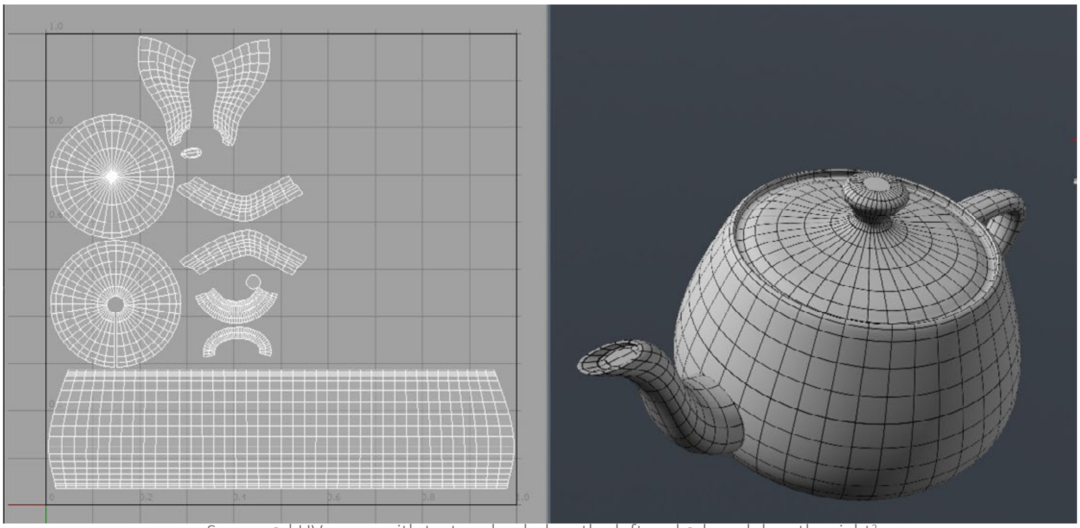
Given this variety and divergence, **texture** is the term that describes the **sum of the visual attributes** of a digital model: colour, relief (normal direction or altitude/bump), reflectivity, etc.

The process of assigning values to these attributes is termed "**texturing**". The information about each visual attribute is provided by the user to the modelling software by means of raster images, which can be either of photographic or illustrative origin. Raster images are practical for this purpose, exactly because of their data structure: they are used as a **matrix with intensity values.** Therefore, to describe factors with a single parameter, greyscale images are used as intensity maps. For factors with 3 parameters, RGB coloured images are used, since they contain 3 channels of information.

UV Mapping

Since raster images are used to attribute intensity values to each 3d point of the object, a **correlation between 2d and 3d coordinates is needed**. This process of projecting the polygonal 3D surface of a model on a 2dimensional plane is termed "**UV mapping**". The 2d coordinate system is symbolized as UV (instead of XY), to differentiate from the world space Cartesian Grid System which uses the XYZ symbolism. UV space is finite and is always of square dimensions and with [0-1] range of values.

This projection is arbitrary and depending on the particularities of the object's geometry and its purpose of use. The procedure can be manual or automated. For complex surfaces, it is common that the 3d surface is divided in **surface groups**, which are distributed on the UV space, leaving **unassigned areas** in between them[1]. Choosing which UV mapping configuration is **optimal** depends on minimizing the empty space between surface groups, minimizing distortions and producing well-placed seams.



Square 2d UV space with texture loaded on the left and 3d model on the right[2]

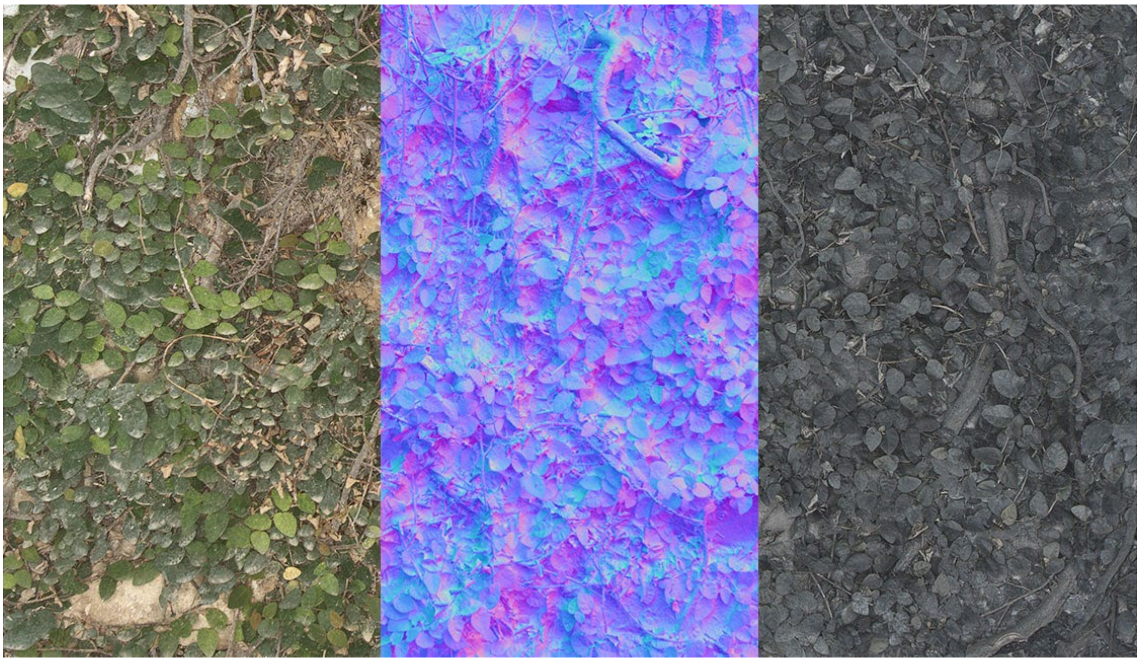
1 In order to avoid sharp transitions/image boundaries, the space inbetween is filled by a mean colour average.

2 http://www.renderspirit.com/wireframe-render-tutorial/

Texture maps

Diffuse Map

The diffuse map is the most common kind of texture map and determines the colour information of the model.



Diffuse, Normal Map and Bump Map of the same model[1]

Displacement map & Bump Map

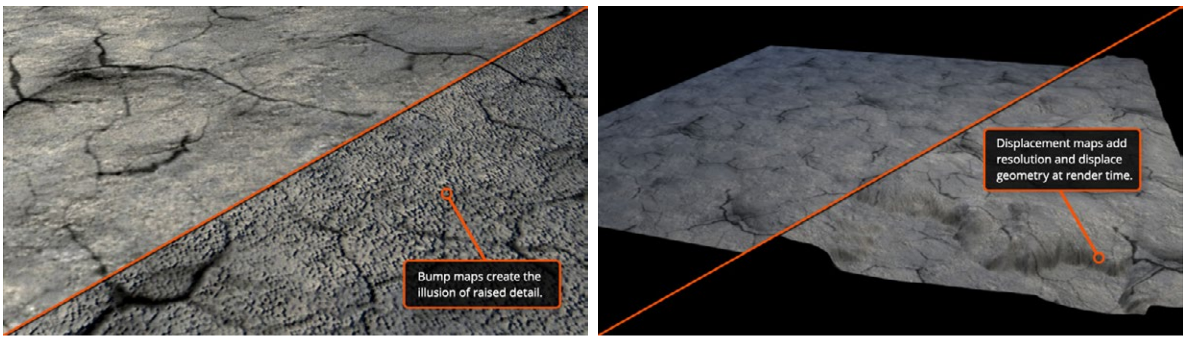
Bump maps & displacement maps are both greyscale images used in the texturing process of digital models in order to give a sense of **depth/relief**, thus enhancing the photorealistic appeal.

Bump maps create the illusion of depth on the surface of a model by using greyscale levels to offset the position of the normal vectors.

Displacement maps are also greyscale images that contain relief information, but displacement maps, in contrast to bump maps, actually deform the object’s geometry by push / pull actions, when applied.

Commonly, a combination of the two is used, where displacement maps offer the medium-level relief information and bump maps the finer-level/simulate the appearance of fine details.

> It should be noted that both of these map types are **not produced or used in a photogrammetric project** *and should not be applied to photogrammetric derived models.*



Distinction between bump map (left) & displacement map (right)[2]

1 http://quixel.se/megascans
2 http://blog.digitaltutors.com/bump-normal-and-displacement-maps/

Viewpoint

Navigation in digital modelling software is available through simulation of a **viewpoint** in digital space. A **virtual camera** can be positioned at a desired viewpoint in order to create a 2d image of the digital 3d scene, in direct analogy of capturing a photograph in physical space. The spatial location and orientation of the camera in digital space is termed **viewport**.

The scene visible from each viewport depends on the camera - target model spatial configuration, in terms of viewing angle and distance. The visible scene is then rendered by the rendering engine, thus creating a raster image. This means, of course, that by changing viewports, multiple images of the same target model can be created.

Viewpoint Maps

The most common type of images rendered this way, are the **photorealistic images** that make use of the assigned texture of the model. They are therefore the closest analogy to a photograph of a physical object. Apart from this, however, other types of raster images can be computed, that are termed -again- as **maps**, since they too offer a correlation between the intensity values of a parameter and the intensity values of the channel/s of the created image. This time though, these maps are an output of the software instead of a user input.

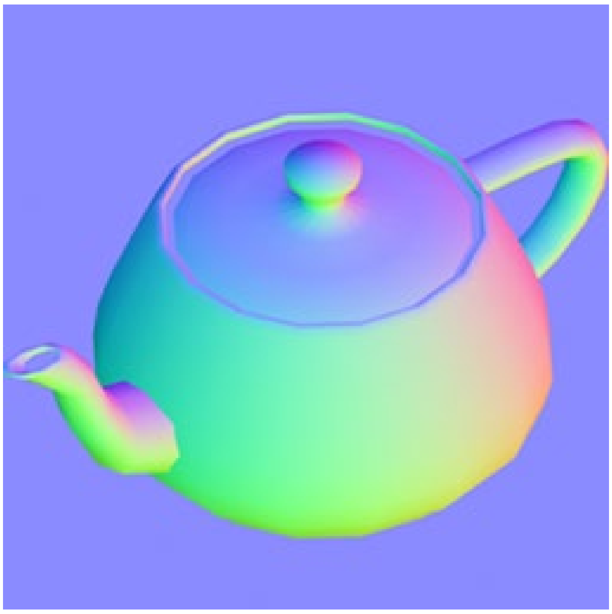
The 2 most important to photogrammetry types of viewpoint maps are **normal maps** & **depth maps**.

Normal map

A normal map is a **colour image** that provides information about the **orientation of the normal vector** for each polygon with the relation to the optical axis of the camera. Each of the R,G,B colour channel values of a given pixel corresponds directly with the XYZ rotational angles of the normal vector of the corresponding point.

Depth Map

A depth map, also known as Z-depth or Z-buffer, is a **greyscale image** that contains information related to the **distance of points from the viewpoint**.



Example of a Object Space normal map on the left[1] & Depth Map on the right[2]

1 http://www.java-gaming.org/index.php?topic=27516.0
2 http://3.bp.blogspot.com/-L2lfrItAJq8/UJgegiEyUaI/AAAAAAAAOfU/QrMDJINUQQo/s1600/teapot+8.JPG

SECTION C)
IN PRACTICE

<Abstract>
In this chapter, we will cover a full walkthrough of a close-range photogrammetric project.
We will start with the importance and the details of the planning process: setting goals & desired output, choosing suitable equipment, software & general setting.
Next, we will discuss in detail the image capture stage, which is of great importance for the quality of the outcome.
We will overview the different software alternatives for the actual photogrammetric procedure.
Finally, we will close with available options on using the output.

CONTENTS

PLANNING A PHOTOGRAMMETRIC PROJECT

Factors to take into account when "designing" a new project:

For a successful project, a balance between the following 3 parameters needs to be achieved: the team's "strength", the object's "difficulty" and the goal's "challenge". These can be analysed in the following factors:

Team Capabilities	Skill Proficiencies
	Cost/Investment
	Available Equipment
Object	Photographic Set-up / Environmental Conditions
	Object Properties: Size / Location / Material / Colour
Deliverables	Intended Use:
	Desired Resolution
	Desired Types of Output (file formats)
	Desired Accuracy & Precision

General tips on project management

Photogrammetry is not an art of "black and white", meaning that for establishing the threshold of success, an approach of "good enough" is the way to go. Keep a balance between the effort you need to invest (in both terms of time and expenses) and the challenge level of the goal that has been set. Start by determining the intended use and what it demands in terms of level of detail and file formats. Estimate the precision of your system and prescribe a threshold of accuracy that is adequate for the needs. Assess the "difficulty level" of the task by examining the properties and suitability of the object and plan the photographic capture accordingly. Keep only high quality photographs and strike a balance between amount and resolution/size of images. Unnecessary excess will only delay processing times and burden your project. Likewise, set your bundle adjustment and point cloud/mesh creation process setting at a suitable level that can guarantee the quality of output but remember that higher resolutions may prove unwanted and lead to even more problems. This "balance" is hard to assess beforehand and can be determined by trial and error based on project specifications, but also by experience.

Clear understanding, forethought and planning can greatly improve the quality of results, but keep in mind that photogrammetry in general is a practical art that will require multiple trial & error efforts. Thus, attaining "hours of flight" / experience are of great importance. For new users, remember to start small and build up in order to better troubleshoot errors, keep a log of the experimentations, archive the generated images and files and manage their metadata. Stay alert for possible unexpected factors that can undermine the quality of the outcome each time and be ready for improvisations. For these reasons, it can be stated that an "engineering" mentality or background is a useful asset.

WORKFLOW OVERVIEW

I. Studying the Object

The first step is inspecting the object to be documented and noting the specific **properties** that are of importance to the photogrammetric process. As a result of this, there can be a rough estimation of the **difficulty level** of the task. Detailed notes about each step follow.

II. Defining Level of Detail

The next decision step is stating the desired **Level of Detail**. This means deciding on the smallest feature of the object that should be recorded, which in its own turn is based on the intended scale/resolution[1] of the final model. The level of detail will determine the **Ground Sampling Distance** (GSD), which in turn determines the suitability of available equipment or guides the equipment selection process (and/or defines an acceptable range of shooting distances). The GSD also is a parameter that affects the level of **accuracy** of the documentation result.

III. Choosing a photogrammetric workflow approach

At this step, an important distinction between the two available photogrammetric workflow approaches is made: between **semi-automated** (Stereophotogrammetry) and **automated** (Multi-View Stereo). This is the first decision step in the planning of a project and will affect decisions and techniques at all the later steps.

IV. Image Capture

The image capture step is a very important process that can take up a great amount of time and effort. It is imperative to **comprehend the rules** governing the photographic capture, since the quality of the input will determine the quality of the result. The specific rules and details of image capture depend on the chosen photogrammetric approach, as will be presented later on. If deemed appropriate, even collaboration with external parties/professional photographers can be of benefit, as long as the project management team can guide the photographer throughout the process to ensure delivery of "photogrammetrically-suitable" material.

The Image Capture process can be divided in **Preparation** stage and actual **Photo-shooting** stage. Preparation includes the selection process of photographic equipment and the set-up of the photographic stage, if shooting indoors. In the photo-shooting chapter, details about camera settings are explained and camera positions for both workflows are presented and compared.

Finally, **Post-Processing** of Photographs is presented as an additional & optional step that can include various tasks, depending on the situation.

1) Preparation

- *Choosing Equipment and Accessories*
- *Setting up the stage*

2) Photo-Shooting!

- *Camera Settings*
- *Camera Positions*

3) Post-processing of Photographs

V. Photogrammetric Process

The preparation step involves **choosing and gathering** of the equipment, in terms both of **hardware** and **software**, not only for the photogrammetric process but for all digital steps (including image manipulation, photogrammetry, cloud/mesh/model editing, etc.). The particularities of the **data process i**n itself depend

1 For more information, please see the corresponding chapter in section B.

on the chosen workflow approach and on the employed software, but the rough steps of the process are common in their succession. Emphasis will be given on the **automated approach** and the steps of this workflow will be presented **in detail by means of an example application**.

VI. Using the Data Export/Post-Processing

Depending on the needs, the project can result in a combination of any of the following important photogrammetric products:

- *Dense Point Cloud*
- *Stereomodels*
- *2D Vector Drawings/Plans*
- *Orthoimage/Rectified Photographs*
- *3d Object Models (with or without texture)*

Some common scenarios on making use of the photogrammetric products will be presented in short.

I. STUDYING THE OBJECT

Type of object

Every project starts by studying the object's properties. The first level of discrimination for a project is the **type the object**:

- **Setting.** An arrangement of unmovable objects, that needs to be documented in its original surroundings. It could be natural scenery (rock/cave formations, tree forest, etc.) or a man-made establishment (building, structures, machinery, etc.). That is also the case with relatively large and heavy items objects that cannot be transported.

**Special cases might include small objects that cannot or should not be touched/removed from their natural environment, such as living organisms (flowers, mushrooms, plants) or fragile formations, etc.*

- **Object/object collection.** An arrangement that can be transported and positioned in a designed set-up for photographic capturing.

** In this presentation, we will exclude moving targets.*

Photo-Shooting Location

The type of the object therefore also determines the **photo-shooting location**.

It is obvious that in cases where the photo-shooting needs to take place **on site**, a higher degree of complexity is to be expected.

One may need to deal with issues, such as **accessibility of the location** and/or of enough **surrounding space for operation**, whether it regards the closest or farthest possible reach for adequate photo-shooting or the inability for full, 360° coverage from all heights. All of this will have a definite influence on the **choice of equipment** in terms of camera type and portability, lenses and necessary accessories.

**Extreme cases, such shooting at night-time/low-light shooting, underwater locations, etc. might require special cameras or filters.*

Also important are the **variable external influences**, such as variations in lighting conditions, weather influence, movable targets, occlusions or other impediments to photographic capture. These factors need to be resolved with studying the conditions and planning the shootings with forethought, multiple visits, surplus of data, possible need for co-operation with other parties and in general, a high degree of improvisation and problem solving, as mentioned.

All of these possibly detrimental factors can be omitted, if the photo-shooting can take place in a **controlled environment** (such as photo studio/laboratory).

Size of object

The next level deals with the **size** of the object. This will influence the **space requirements**, the possible need for a **special mechanical set-up** for the full coverage of the target, the **time** required as well as the **amount of images**. Special cases regarding size might involve the need for **special lenses**, such as for macro photography, etc.

Physical Properties

The next level refers to the properties of the object and is used for assessing its difficulty level/suitability. Defining properties are the **material**, the **texture**, the **colour** and the **form/shape** of the object.

Detrimental to a successful output are object properties such as:

- too densely textured or adversely, too low / featureless
- transparent material or material internal refractions
- darkly coloured with high light-absorption
- *shiny or glossy surface/high specular light reflectivity:* Specular reflections of glossy surfaces are view-angle dependent and can thus lead to mistakes in the image matching process.

** In cases where it is allowed, keep in mind that painting or chalking the object can help amend for short-comings, for example to pronounce a low texture or hide excessive glossiness, but expect also an increase of overall uniformity, which in itself is another detrimental factor.*

Avoidable objects are not textured, completely flat, very thin, transparent, shiny, and/or reflective. Examples of difficult-to-capture objects are leafy plants, fur and hair, glass items, and shiny or sparkly ornaments. Conversely, **suitable** objects are solid, matte, textured, ideally with large and small levels of detail.

II. DEFINING LEVEL OF DETAIL

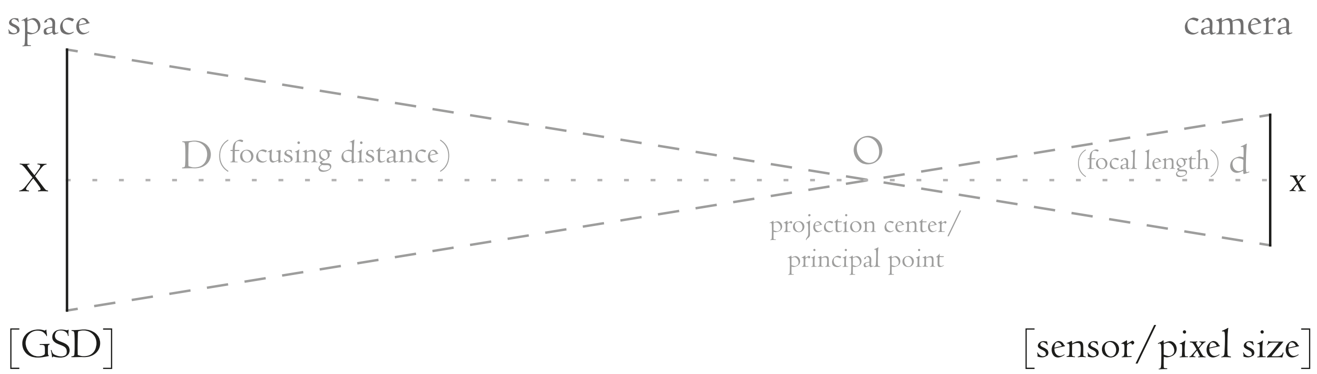
As already stated, the **Level of Detail** defines the smallest feature of the object that should be recorded and depends on the “drawing scale” of the final geometry. The length of the smallest feature needs to be equal to the **Ground Sampling Distance** (GSD), that is the distance of two pixel centres projected on the object.

As shown below, the GSD is a **three-way balance** between:

- **shooting/focal distance**
- **focal length** of available lens
- & **pixel size** of the camera image sensor (sensor physical size / sensor pixel resolution)

The GSD will judge the suitability of available equipment in terms of camera resolution and lens’ focal length or guide the equipment selection process and/or define an acceptable range of shooting distances.

Ground Sampling Distance



Length of smallest feature to be recorded on Object == Ground Sampling Distance: X
Focus Distance: D
Pixel Size (square pixels): x
Focal Length of Equipped Lens: d
*D/d = X/x > X = x*D/d*
*> GSD = Pixel Size * Focus Distance / Focal Length*

Resolution of Camera’s Image Sensor

The image sensor of the camera needs to have adequate **resolution** to cover the desired GSD. This is a challenge in cases where there is a need for a relatively large shooting distance from the object, since nowadays, most cameras offer adequate pixel resolution for a photogrammetric project. Nonetheless, checking and establishing conformity is advised.

Calculating Pixel Size

Pixel size is defined by the ratio of the sensor’s physical size to the (max.) image resolution.

** Sample Camera: Canon EOS 5D Mark II*

Sensor Type:	*CMOS*
Effective Megapixels:	*21.1*
Sensor Format:	*35mm*
Sensor size:	*36.00mm x 24.00mm*
Focal Length Multiplier:	*1.0x*
Aspect Ratio	*3:2*

Sensor Type:	*CMOS*
Image Resolution	*5616 x 3744* *4080 x 2720* *3861 x 2574* *2784 x 1856*
ISO range	*100-6400*
Shutter Speed	*1/8000 to 30 sec.*

** In the above example, the calculated pixel size of the camera is 0.0064mm (36mm/5616 pixel).*

**The aforementioned full-frame camera with 0.0064mm pixel size, if equipped with a 50mm lens and when shooting at a focal distance of 1m., will be able to record a detail of maximum size 0.128mm.*

III. CHOOSING WORKFLOW APPROACH

Photogrammetric workflows can be divided in two basic "types": the one can be described as the more "**traditionally photogrammetric**" or "**stereophotogrammetric**" approach, where processes demanding a sounder control and deeper understanding are required. The other would be the more automated and user-friendly "**computer vision**" or "**Multi-View Stereo**" approach, since it is based on the implementations of computer vision algorithms. In practical terms, they differ in the degree of user skills, control and input, since both result in the same output and can yield results with the same accuracy, given appropriate planning.

" Traditional Photogrammetric" / Stereophotogrammetry / Semi-Automated

- *Network Design / careful planning of photo-capturing locations, including:*
    - Estimation of Ground Sampling Distance/Image Scale
    - Calculation of required Base (Capturing distance from target)
    - Orientation of optical axis in relation to object surface
    - Parallel optical axis between photo-shootings
    - Adequate overlap between photographs
    - Ideally, minimizing the required amount of photos
- Calibrated Camera / known interior orientation parameters
- Use of appropriate software equipped with analytical processing of collinearity condition
- Interior - Exterior, and Relative orientation for 3d Point restitution
- Absolute orientation for georeference of object and estimation of correct scale (with geodetically measured Ground Control Points)

"Computer Vision approach" / Multi-View Stereo / Automated

- Greater degree of flexibility / Not rigid planning requirements of photo-shooting
- Surplus of photographic input ("over-coverage" of target)
- Minimum requirement for 3d restitution is that the same point appears in at least two images
- Shooting from various distances for desired Level of Detail
- No requirement for Ground Control points, need for a known length measurement (either on target or by using a scale bar) or a known base (camera distance)

The first decision-making step is the **selection of approach**, as stated either automated or semi-automated. In specific cases, the **properties of the object** will determine the suitable approach. An extreme example of this, is when the object's location does not allow an adequate photo-coverage with the prerequisites of the traditional approach. Otherwise, the choice between the two is up to the **preference of the user**, depending on his acquired skills and the availability of equipment, in terms of both hard- & software.
Keep in mind that the chosen approach will also determine the range of available software choices and that the availability of open source software in the computer vision approach is significantly greater.

> > In this presentation, focus will be given on the "Computer Vision" approach, since it is deemed by far the most user friendly and in active development for the future.

Overview of "Traditional" Approach

1. Camera Calibration or Explicit Knowledge of Interior Orientation
[either via camera calibration methods |or| camera metadata from EXIF and application of average description from a library of known interior orientations, usually supplied by camera manufacturers]
2. Designing the network
3. Digital Image Acquisition
4. Field Data Acquisition / Ground Control Points Measurements
5. Image Processing (optional)
6. Input of Images, Input of Ground Control Points & Tie points
7. Block Orientation
8. 3d Point Restitution
9. Generation of desired Products (Mesh/Orthophoto)
10. Data Export

Overview of "Automated" Approach

1. Photographic Capture
2. Optional Image editing (such as masking)
3. *Input in photogrammetric software for bundle adjustment:*
    1. Loading and assessing photographs
    2. Alignment of cameras
    3. Sparse point cloud generation
    4. Dense point cloud generation[2]
    5. Polygonal mesh generation
    6. Texture generation
4. Data export

2 May be skipped if a polygon mesh is to be calculated in external software.

IV. IMAGE CAPTURE

Digital Photogrammetry is a good example of the GIGO[3] principle, therefore careful **planning of the image capture** and **quality control of image data** should precede the bundle adjustment stage.

Understanding the fact that a **rule-based approach** is needed to the photographic capture stage is vital: *"To perform high-quality photometric measurement, the photographer capturing the photogrammetric data set must follow a rule-based procedure. This procedure will guide the user on how to configure, position, and orient the camera towards the imaging object in a way that provides the most useful information to the processing software and minimizes the uncertainty in the resulting measurements."*[4]

Image Capture Rules based on Photogrammetric Approach

Although the desired image qualities (sharp, balanced, etc.) are the same in both photogrammetric approaches, the rules governing the camera shooting positions vary greatly. Details about the image capture rules for an automated project will be presented and briefly contrasting with rules for a semi-automated project.

Photogrammetric Rules regarding image capture revolve around:
a) Quality of shot photographs
b) Spatial relationship of camera locations with regard to the object and its other.

3 Garbage In, Garbage Out. https://en.wikipedia.org/wiki/Garbage_in,_garbage_out
4 http://culturalheritageimaging.org/Technologies/Photogrammetry/

CHOOSING EQUIPMENT

I. Choosing Cameras

Camera Types

Depending on the required final quality of the 3D model various types of camera can be used: professional **metric cameras** for high precision measurement, more affordable but still reliable **DSLR cameras**, low-cost **compact cameras** or even **mobile phones' cameras**. Leaving the extreme range off examination (metric cameras and mobile phone cameras), we can compare between the two more affordable alternatives: digital SLR cameras and compact digital cameras.

DSLR (stands for digital single-lens reflex camera) tend to give far better results than compact digital cameras. Digital SLR cameras are generally equipped with higher quality lenses than compact cameras, a fact which testifies to the better results. Apart from that, DSLRs can benefit from interchangeable lenses, thus offering more flexibility. In addition, digital SLR cameras normally provide more controls for image capture, so tend to be more versatile and hence capable of tackling diverse problems. Such cameras are also equipped with better and larger sensors offering high ISO performance, another factor for good imaging quality. Furthermore, DSLRs have the ability to store the images directly into RAW file format thus allowing for better histogram correction. Another category of digital cameras, which is slowly rising to prominence since 2012, are mirrorless interchangeable lens cameras (**MILC**). They have the same characteristics with a DSLR in terms of sensor quality and lens range, but substitute the mirror reflex optical viewfinder with an electronic one. This enables for a smaller, more compact and lightweight design at comparable or even more affordable prices than DSLRs.

Camera Image sensor physical & pixel size

As established before, the GSD will determine the need of the camera in terms of **resolution**. Although the number of megapixels of the sensor is an important factor, since higher resolutions provide more information, it should not be the only & primary regard. The actual, **physical size of the image sensor** needs to be proportional to the image sensor resolution, i.e. for a given resolution there is a comparative loss of quality in smaller-sized image sensors due to physical limitations. Therefore, sensors with capacitator/pixel size of less than **0.004 mm** (4μm) should be avoided.

> Regardless of resolution, if the equipped **lens** is of low quality, images will lack sharpness and clarity whatever the resolution. Therefore, choosing a high quality lens will also impact image quality. Guidelines on choosing the appropriate type of lens follow.

II. Choosing Lenses

Fixed over Zoom Lenses

It is advisable that the distance of the principal point to the image sensor remains constant in photo shooting. Therefore, it is preferred to use a **fixed lens** over a lens with a zoom function (variable focal length). Even though variable zoom lenses are more versatile and can be especially useful in close range photogrammetry, bundle adjustment with a single focal length for the image input is more reliable to compute. If only a zoom lens is available, it is advisable to keep the zoom function steady at a given value during a photo-shooting (e.g. by taping the lens). Also it should be noted that interior orientation camera parameters should be calculated for each different focal length of the zoom lens used.

Camera with 3-axis leveller and zoom lens, taped at chosen focal length

Choosing focal length

For small to medium sized objects, a good **normal lens**, e.g. 50 mm lens is advisable (corresponding to a full frame camera). Ranges of focal length from 20-80 mm are also appropriate. Although wide angle lenses typically allow for better results due to perspective distortions, extremely wide angle lenses (**fish-eye**) should be avoided because of large radial lens distortion values, which reduce the potential accuracy of the system / cannot be modelled. If the object size or level of complexity is so extreme, as to require the use of a **macro lens**, keep in mind that this type of lenses usually have a small depth of field and add excessive areas of blurriness that will be detrimental to the process.

Sample Lenses

>Wide-angle Lens
** Sample Lens: Canon EF 24mm f/2.8*

Lens Construction	*11 elements in 9 groups*
Focal Length	*24mm*
Aperture	*Maximum: f/2.8* *Minimum: f/32*
Angle of View	*84°*
Minimum Focus Distance	*0.20m*

> Normal Lens
** Sample Lens: Canon EF 50mm/f/1.4*

Lens Construction	*7 elements in 6 groups*
Focal Length	*50mm*
Aperture	*Maximum: f/1.4* *Minimum: f/32*
Angle of View	*46°*
Minimum Focus Distance	*0.45m*

> Tele Lens
** Sample Lens: Canon EF 200mm f/2.8*

Lens Construction	*9 elements in 7 groups*
Focal Length	*200mm*
Aperture	*Maximum: f/1.8* *Minimum: f/32*
Angle of View	*12°*
Minimum Focus Distance	*1.5m*

> Macro Lens
** Sample Lens: Canon EF 100mm f/2.8L > Macro*

Lens Construction	*15 elements in 12 groups*
Focal Length	*100mm*
Aperture	*Maximum: f/2.8* *Minimum: f/32*
Angle of View	*24°*
Minimum Focus Distance	*30.48 cm*

Sensor Format & Lens Combination

Using a cropped image frame with a full frame lens can have the benefit of cropping out **optical vignetting**, which appears as a gradual and often subtle darkening away from the image's centre. Optical vignetting is typically most apparent at lower f-stops, with zoom and wide angle lenses, and when focusing on distant objects.

III. *Choosing Additional Tools*

Tripod

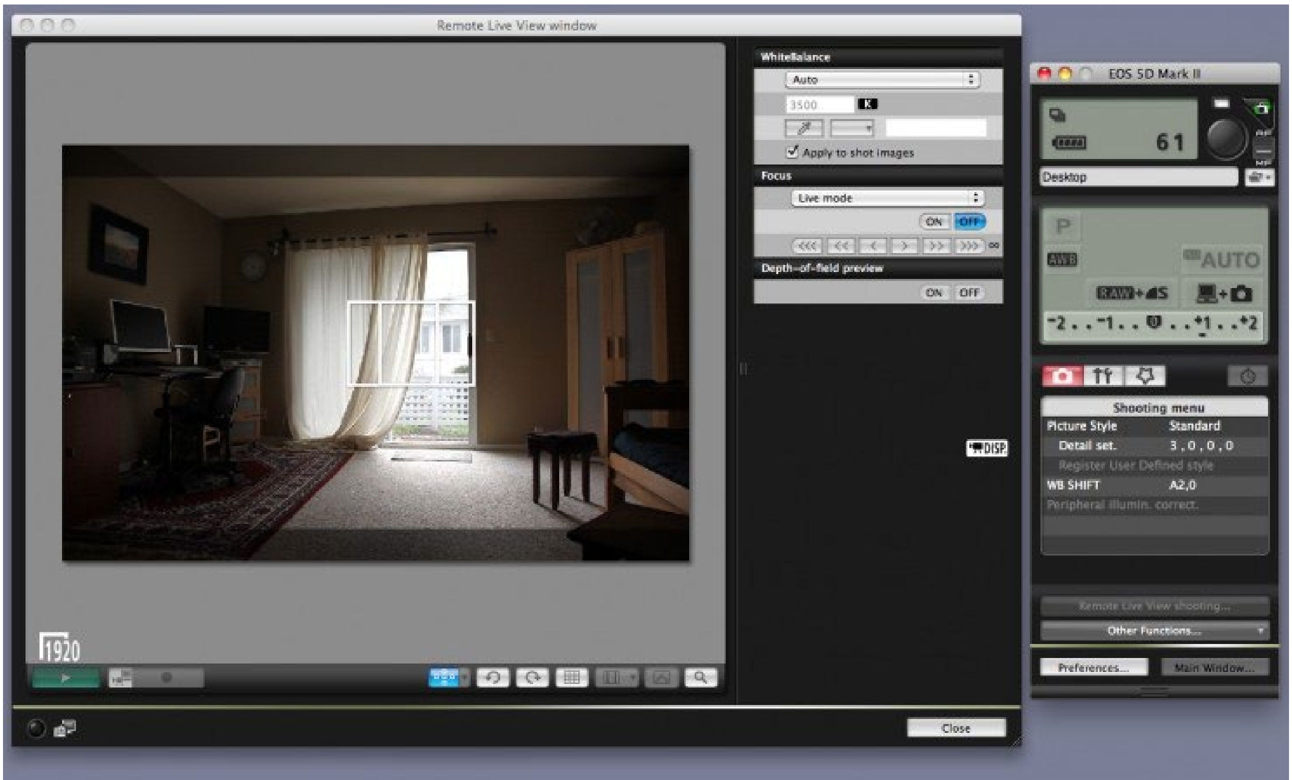
Tripods are of outmost importance in photogrammetry for getting a proper, sharp image, eliminating blurriness due to user instability. Tripods prove especially useful when setting larger f-stop values in order to achieve maximum depth of field, since this usually needs to be compensated with longer exposure times. The extensible height of a tripod is also an asset while photographing the object from higher/lower angles.

Remote shutter release

Remote shutters further remove shakiness during photo capturing. The same effect (remote shutter release) can be achieved without the extra cost of a hardware remote by installing appropriate **software** on a computer and connecting the computer with the camera via different methods, as supported by the camera, simplest of all via usb. On the other hand, this setting adds the extra requirement that a laptop or desktop can be positioned near the camera and in cases of wired connectivity, there is a also limitation on camera mobility.

Professional software for this purpose is available at a price, free to use alternatives can be downloaded from the web and camera manufacturer sometimes provide their own software version. Please look for appropriate resources according to your equipment.

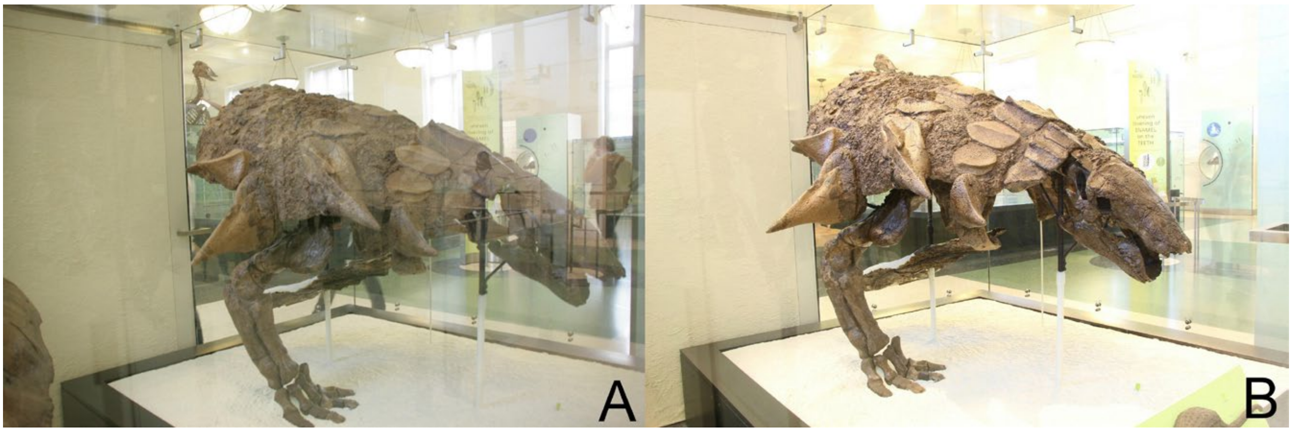
Free to use software: http://digicamcontrol.com/



Canon EOS Utility with Remote Live View and shutter release

Circular polarizing filter (CPF)

Depending on the type, location and environment of the object, **polarizing filters** can be a great investment, making achievable otherwise impossible photo-captures. Their main effect is the reduction of glares and reflections. Keep in mind that CPFs will not be ineffective on material glossiness, such as metallic surfaces.[5]



without (A) and with (B)effect of using polarizing filter[6]

Leveller

Although not a requirement, a leveler can be useful to estimate the current angle while photographing the object from different heights. For the needs of photogrammetry, a detachable 2/3-axis leveller (used in conjunction with a tripod) can prove a useful addition.

Flash

Flash is best to be avoided due to its directness. Stable, diffuse, environmental lighting should be preferred instead. If illumination still remains adverse, a studio flash should be used.

5 http://blog.sketchfab.com/post/121838008009/how-to-set-up-a-successful-photogrammetry-project
6 http://www.jpaleontologicaltechniques.org/pasta3/JPT%20N12/Bulletin_intro.html

SETTING UP THE STAGE

In cases where the object is a small to medium sized object that can be handled and placed in a stage, there is the opportunity to design and provide an adequate photo-shooting environment.

Placing the object

Ensure 360° **unimpeded movement** around the object.

Since only imaged parts of the object can be traced, it is important to place the object in a suitable position for **maximum coverage**. Depending on the situation, ideally raise the object on a pedestal, in order to be able to shoot **from all angles**, including lower ones.

Using a Turntable

An alternative to moving around the object for 360° photo coverage is the use of a turntable, suitable for the size and weight of the object. Although ideal for cases of **space narrowness**, this setting can prove advantageous nonetheless. It will allow for a **stable camera position**, which in turn can save on the relocation of the tripod and also offer the choice of remote shutter release by connectivity to a computer.

DIY turntables can range from very simple (hand rotation based on some degree marks) to very sophisticated (automated). Ideally, a set-up that makes use of a suitable board, a gear combination, a servomotor and a micro-controller such as an arduino, can offer **controlled, stepwise rotation of the target**, with clear knowledge of the rotational angle.

> construction guidelines for a DIY automated turntable, here[7]:
https://microcontroller-projects.com/arduino-rotating-photo-table/

Lighting conditions

Lights are a definite requirement in most indoor shooting projects, but also in advantageous cases of the exterior shootings. In any case, for special cases, please examine beforehand the sensitivity of your object or of its environment to light exposure and also heat generation (depending on type of light bulbs).

The lighting should ideally be fully controlled, meaning external light, which shows great fluctuations, should be avoided. Lighting sources should be situated all around the object, so that it is evenly lit on all sides and that shadows on the object are kept to a minimum. Excessive lighting should be avoided though, since small shadows assist to pronounce the texture of the object. A common set-up is the use of 3 light sources in a triangular formation. Soft and flat lighting is desirable - therefore lights should not be directed straight-ahead at the object but rather on surrounding space surfaces so as to offer ambient illumination. Another choice is the use of a suitable material/screen for light diffusion (such as shoot-through umbrellas).

These neutral lighting conditions are necessary, so that the textures can be seamlessly fused, on the one hand, and on the other, so that the final model does not have “embedded” a pre-established lighting condition, which could limit its practical usefulness.

Furthermore, setting the lights in a particular way that creates shadows on the surrounding surfaces but not the object (i.e. higher up and with a downward angle) can be useful, since it can provide more features for the image matching process.

Summing up, **diffuse, 360° lighting** is ideal for interior shooting.

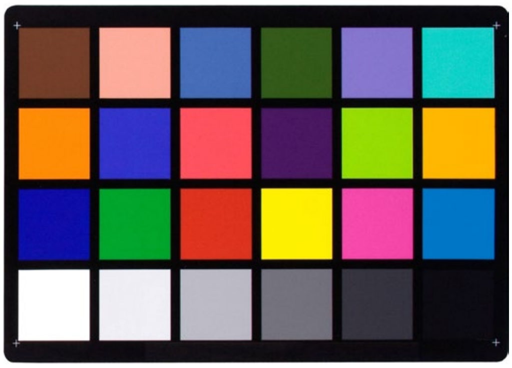
In exterior cases, preferable are overcast/cloudy days and within the same day, mid-morning or mid-evening hours which have uncoloured light of mediocre intensity coming from medium to high angles.

White balance/Colour management

Photogrammetry may primarily deal with geometry, but it also supports the creation of textured models and orthophotographs, therefore correct capture of the colour information of the target is also important. To make up for the colouring effects of lights, the environment and other elements, it is advisable to

7 For other sources and designs, please check the following links:
https://www.youtube.com/watch?v=1BKr1lTh3Dw
https://www.youtube.com/watch?v=cFPJqtcWNSU
https://www.youtube.com/watch?v=pk52n31XMPM
https://www.youtube.com/watch?v=b5qyGFxTOMs

include a **colour checker** in the set-up, as a reference for the correction of the white balance of the images. Any other item deemed suitable may act as a substitute or at the very least, amend by setting the camera's **white balance** according to the choice of light sources(light temperature). If a texture model output is desired, even if accurate documentation of colour information is not of primary importance, a correct colour-management approach is still advised, since extensive guess-work & individual colour correction on the post-processing stage of the photographs will inevitably lead to disparities and a non-uniform appearance.



Example of colour checker card

The ideal background

If the background of the object will be included in the feature matching process (i.e. if the images will not be masked so as to leave only the object), it is imperative that it will also remain unchanged. In view of this, it is suggested to complete the photo shooting in a single session. If the need for additional photos may arise, make sure to keep the set-up uniform.

In many cases, inclusion of the background can be advantageous for the bundle adjustment processing. For this, the background needs to have certain properties. Avoid repetitive patterns and featureless surfaces and make sure unique, varied areas included. For difficult objects, one can support the feature matching process by adding intentionally various **markers**. This can be as simple and low-budget as laying the surface around the object with newspaper prints (non-repetitive pattern with distinct features) or as specialized as using prefabricated targets with unique format.

If masking the object is intended, the ideal background to assist the masking process is a uniform white/black/grey or green **screen**.

Adding Markers/Scale reference

Since photogrammetry is a scale-less technique, it is of use to place an item of known geometry in the scene or markers with a known distance, which will be included in the processing of the images. This will act as a **reference for the final scaling of the model**. Keep in mind that this is not necessary, if a length measurement of the object can be easily acquired.

PHOTO-SHOOTING!

After setting up the stage, the next important step is **setting the camera parameters** and **designing the photo-shooting location “network”.**

“Good” photography = “Bad” photogrammetry

Specific features which are the highlights of artistic photography are completely counter-productive for photogrammetry (e.g. high contrast lighting and/or highlights, wide-angle distortion, selective/shallow depth of field, blurring, grain effect, etc.). A different approach is necessary which defines the shooting locations and the camera settings with view of the algorithm’s needs.

The Goal

Network:

The goal is
a series of overlapping photographs,
covering the whole of the object,
shot at a focusing distance adequate to document the desired level of detail.

Image:

Each photograph should devote
the largest possible surface to the object,
and contain the largest possible amount of sharp areas
at a balanced exposure / contrast.

Un-wanted properties

Network:

Incomplete coverage of object
Unsuitable/Unoptimized shooting distance

Image:

Blur and Grain/Noise
are the most undesirable effects.

Shallow depth of field
Specular/angle depended reflections
Small Dynamic Range

IMAGE CAPTURE SETTINGS

Image Resolution & File Format

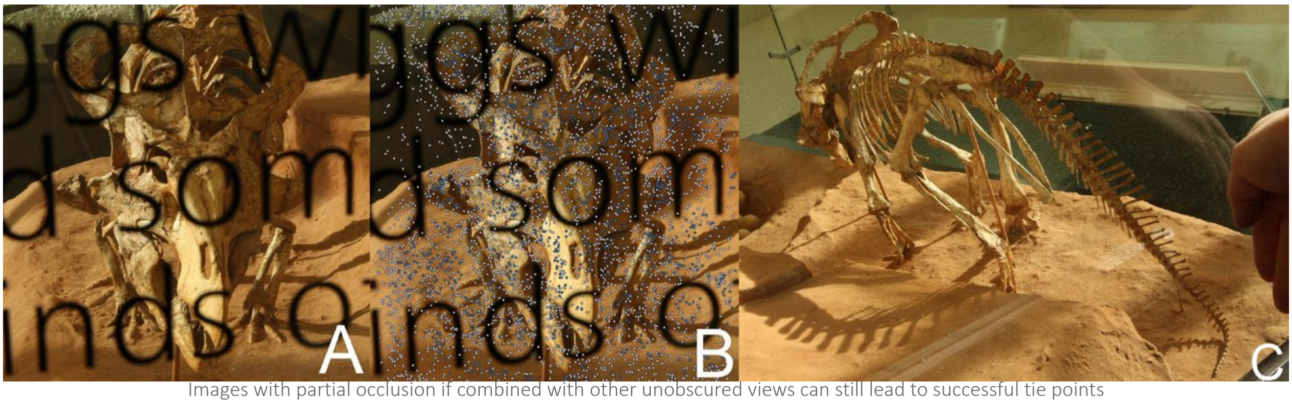
Shooting at **maximum image resolution** is recommended. Images deemed too large for the available computing strength can later be downscaled in appropriate image-processing software or as part of the photogrammetric program workflow. Shooting in **RAW file format** (if available) is advisable, since original data generated by the sensor and therefore maximum amount of information is recorded. Raw files have been considered the only scientifically justifiable file format[8]. They can later on be converted into more flexible image file formats with appropriate software.

Zooming function

As mentioned, it is advisable to use a zoom lens at a fixed focal length. Adjusting the shooting distance can be used to compensate for keeping the zoom steady.

Framing the object

The object must cover most of the image area, thereby making use of the most of the sensor frame. Even if the whole of the object is not visible in one shot from the required distance, taking partial photos with correct overlap is totally acceptable. Also, even if obstacles are hiding part of the object from a given viewing angle (as is the case with specimens behind frames), the photos can still be useful, as long as the occluded parts can be visible from other angles.

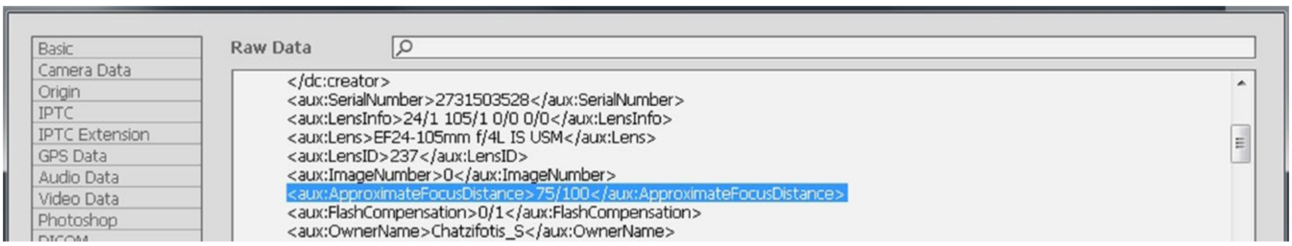


Images with partial occlusion if combined with other unobscured views can still lead to successful tie points

Focus distance

Establishing the shooting distance from the target based on the desired GSD, as mentioned, is primary. Secondly, one can try focusing on the parts of the object that are in the middle of the distance range, so as to achieve maximum exploitation of the depth of field.

Focus distance is recorded on the EXIF data of each capture under the tag <ApproximateFocusDistance> and can be viewed with any EXIF reading software, such as Adobe Bridge/Photoshop, etc.



Auto-focus

Auto-focus is a feature in modern DSLRs that uses phase or contrast detection to set the focal distance at an optimum value, as deemed suitable at each photo-shot by the mechanism. Therefore and in order to keep the photographic parameters as stable and common as possible, it is best to disable this feature and use manual focusing.

8 https://biblio.ugent.be/publication/941064

Stabiliser\anti-shake

It is not recommended to use with anti-shake (image stabiliser) mechanisms that new breeds of DSLRs come equipped with. The anti-shake mechanism adds to a sharper image formation by the compensatory movement of either the lens elements or the actual sensor. These types of features should be avoided in photogrammetric work, where each recorded pixel position must represent a repeatable measurement point.[9]

Shooting Settings:

1) Aperture & Depth of Field

Use a mid- to high-range f-stop for a larger depth of field and maximum sharpness[10].

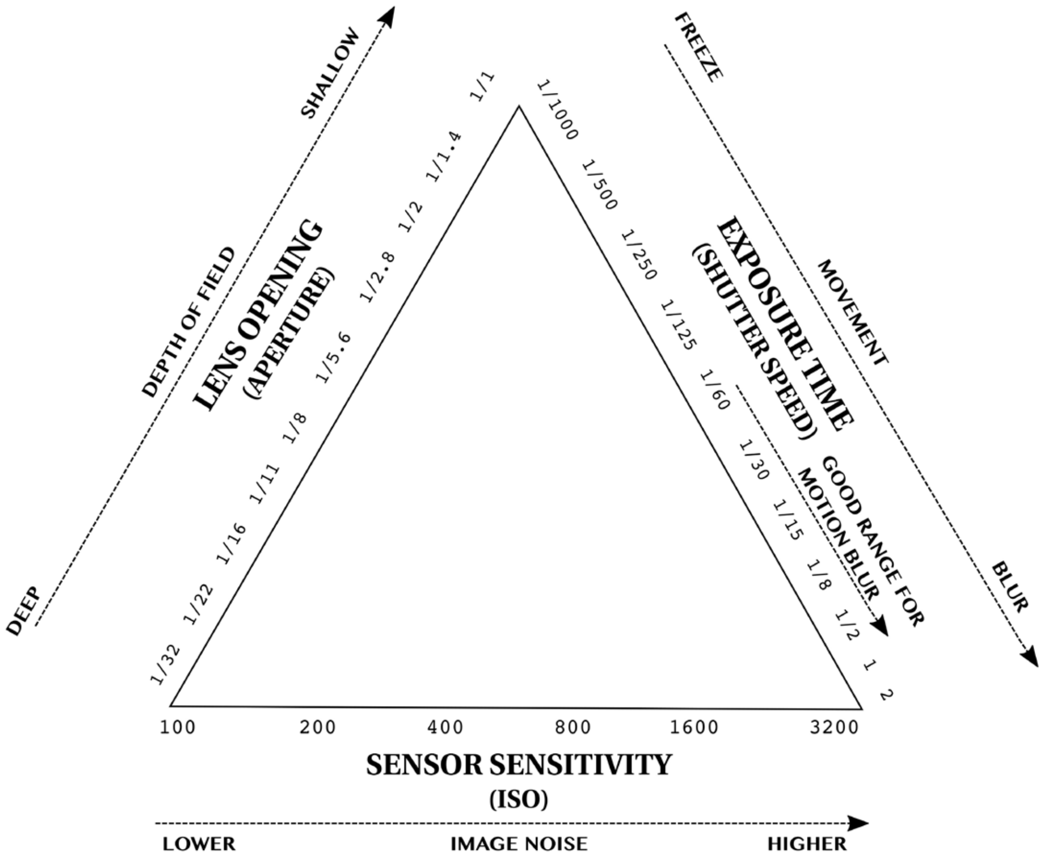
> Depth of field calculator: http://www.cambridgeincolour.com/tutorials/dof-calculator.htm:

2) ISO / sensor sensitivity

Using ISO settings will minimize fuzziness/noise, which is a very important aspect[11].

3) Exposure time

With smaller aperture sizes (larger f-stop values), slower shutter speed/longer exposure time is needed to compensate. A useful reminder is the use of a tripod.



3-way trade off[12]

ISO value, Exposure time/shutter speed & aperture size/ f-stop are a 3-way trade-off, in which the exact best choice depends on the exact circumstances.

9 "Tips for the effective use of close range digital photogrammetry for the Earth sciences"
Produced by: ISPRS - Commission V - Close-Range Sensing: Analysis and Applications Working Group V / 6 - Close range morphological measurement for the earth sciences, 2008-2012

10 For more info, see section B) Aperture size to Depth of Field

11 For more info, see section B) Iso to Noise Relation

12 Edited. Original Image Source: www.learntimelapse.com

IMAGE CAPTURE LOCATION NETWORK

I. Camera Positions in Automated Approach

Image overlap

A large overlap of images, about 80-90%, will help the feature matching algorithms and will ensure all parts of the object are covered in multiple images. A minimum of 60% overlap between photos is advised.

Shooting angles

Depending on the distance from the target, the needed overlap will define an angle of revolving around the object. A rough indication would be about 10-15° for a small to medium sized object.

Shooting Heights

Shooting must be from various height levels so as to capture the whole of the target.

Number of Images

The final number of photos is totally depended on the size of the object and the level of detail. A clear understanding of the rules will result in a valid estimation of the necessary amount. Acquiring a surplus of photos is often more desired than lack of information.

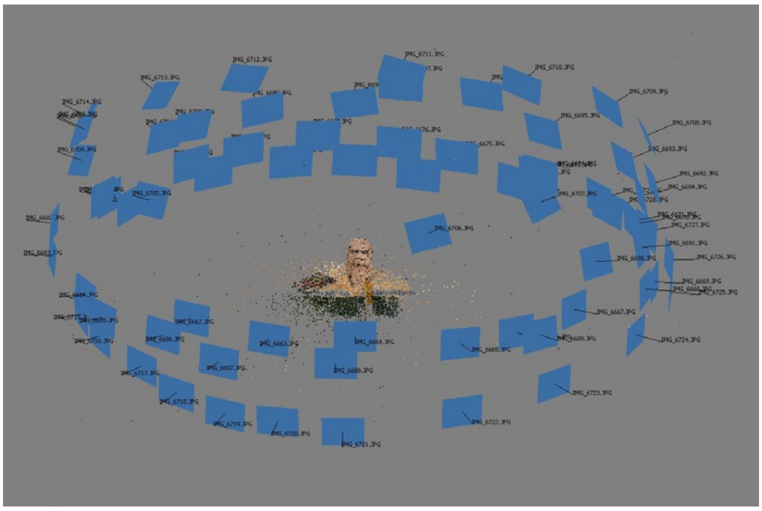
Pre-arranged Set-up

This exemplary set-up includes a rig with **adjustable distance from target** (with stoppers so that the focal distance needs to be set only once and can be common in all pictures), **angle measurement for camera locations** (36 divisions of a circle) and **variable shooting heights** (3 height positions for the camera to have a cover from all angles). Also note **3-point diffuse lighting** set-up. For a single photogrammetric project, this set-up is intended to produce (36 X 3) 108 photographs.

Set-up by Skull Theatre Independent Videogame Studio[13]

Visualization of Locations

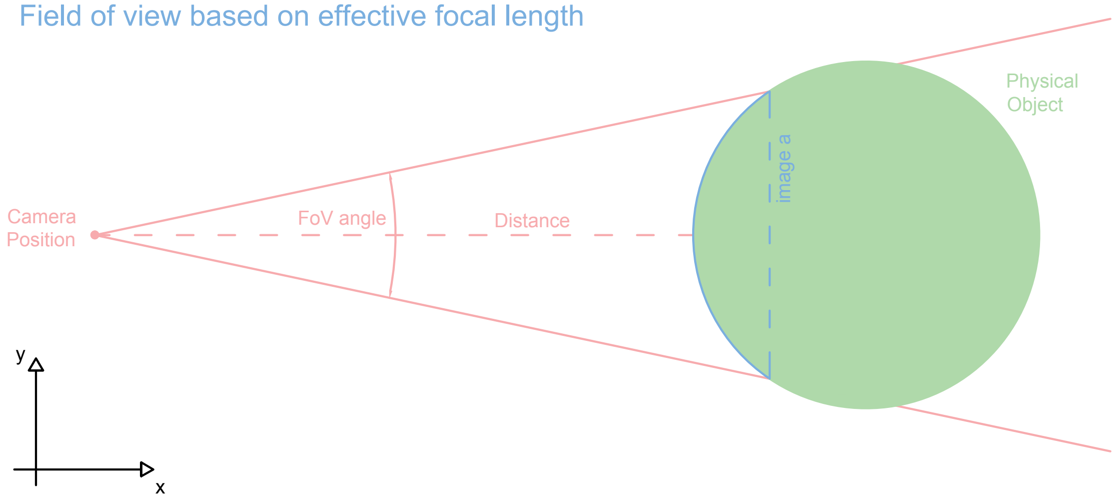
Camera locations can be visualised in the photogrammetric software after camera alignment.



13 http://www.rustclad.com/

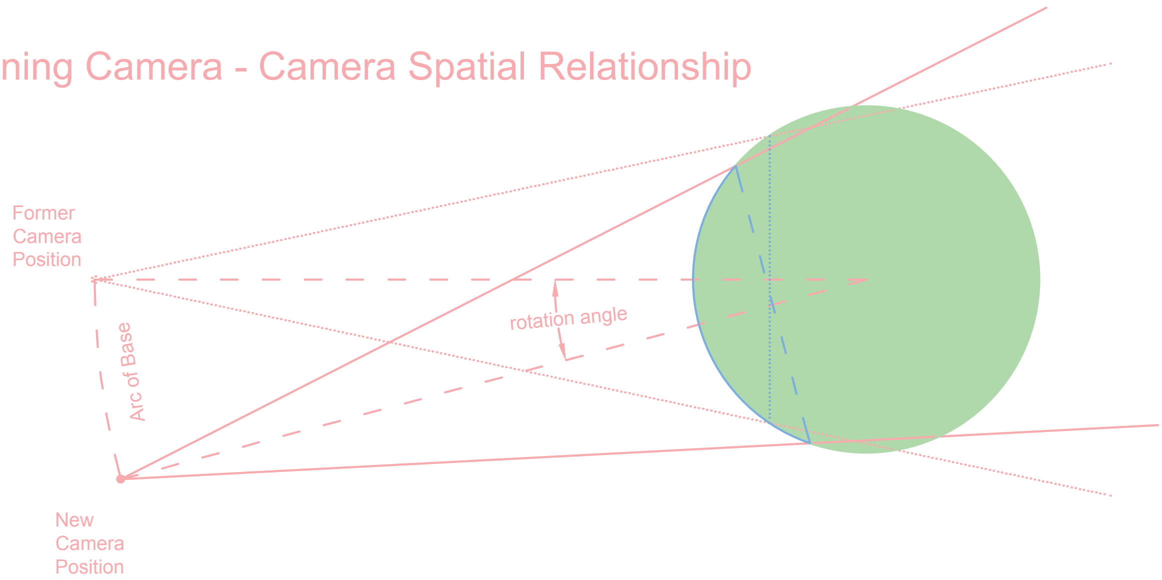
Defining Camera - Object Spatial Relationship

1. Distance from target based on required GSD
2. Field of view based on effective focal length

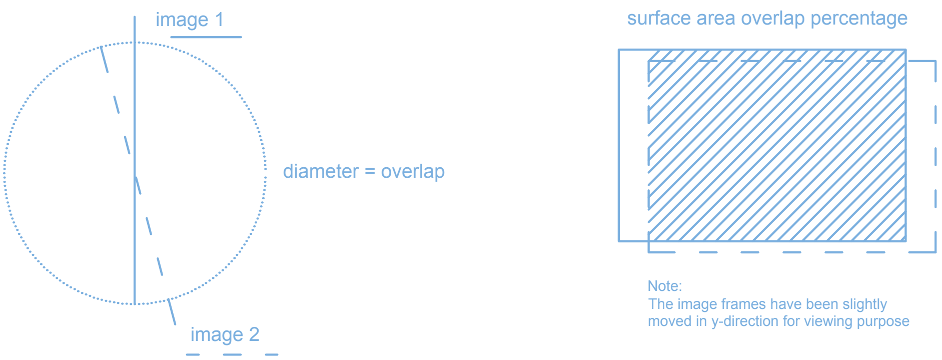


Note: Images are shot from the same height.

Defining Camera - Camera Spatial Relationship



Defining Image Overlap Percentage



II. Camera Positions in Semi-automated Approach

The following rules for photo-capturing are intended with a traditional workflow in semi-automated software and with architectural targets in view. They are listed below for the reader to compare with the much simpler rules of photographic capture in an automated workflow.

“Photogrammetric Capture: the 3X3 Rules[14]”

I The Geometric Rules

1.1 Control

- Measure long distances between well-defined points.
- Define a minimum of one vertical distance (either using plumb line or vertical features on the building) and one horizontal.
- Do this on all sides of the building for control.
- Ideally, establish a network of 3D co-ordinated targets or points from a loop traverse around the building.

1.2 Stereo Photocover

- Take a ‘ring’ of pictures around the object with an overlap of at least 60%.
- Take shots from a height about half way up the object, if possible.
- *Include the context or setting:* ground line, skyline etc.
- At each corner of the object take a photo covering the two adjacent sides.
- Include the roof, if possible.
- No image should lack overlap.
- Add orthogonal, full facade shots for an overview and rectification.

1.3 Detailed Stereo Photocover

- *Normal case (base-distance-ratio 1:*4 to 1:15), and/or
- *Convergent case (base-distance-ratio 1:*1 to 1:15)
- Avoid the divergent case.
- Add close-up ‘square on’ stereo-pairs for detail and measure control distances for them or place a scale bar in the view. Check photography overlaps.
- If in doubt, add more shots and measured distances for any potentially obscured areas.
- Make sure enough control (at least 4 points) is visible in the stereo image area.

II The 3 Camera Rules

2.1 Camera Properties

- Fixed optics if possible. No zooming! Fully zoom-out, Do not use shift optics. Disable auto-focus.
- Fixed focus distance. Fix at infinity, or a mean distance using adhesive tape, but only use one distance for the ‘ring’-photography and one distance for close-ups.
- The image format frame of the camera must be sharply visible on the images and have good contrast.
- The true documents are the original diapositives, negatives or digital RAW equivalents. Set the camera to use its highest quality format.

2.2 Camera Calibration

Use the best quality, highest resolution and largest format camera available:

- ‘Medium’ format is better than small format.
- A large sensor is better than a smaller one.
- A wide-angle lens is better than narrow angle for all round photography. Very wide-angle lenses should be avoided.

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14 First edition: Petter Waldhausl (University of Technology, Vienna, Austria) and Cliff Ogleby (Dept. of Geomatics, University of Melbourne, Australia), at the ISPRS Commission V Symposium “Close Range: Techniques and Machine Vision’’ in Melbourne, Australlia, 1994. Update 2014 by Bill Blake, Andreas Georgopoulos, and José Luis Lerma.

- Calibrate the camera with a fixed focus lens and tape it there.
- Standard calibration information is needed for each camera/lens combination and each focus setting used. Shooting the calibration screen before capture with each lens will help.
- A standardised colour chart should be used in each sequence of frames.

2.3 Image Exposure

Consistent exposure and coverage is required.
- *Work with consistent illumination:* beware deep dark shadows. Use a lighting rig.0
- Use HDR to capture difficult, unbalanced exposures.
- Plan for the best time of day
- Use a tripod and cable release/remote control to avoid camera movement and get sharp images.
- Use a panoramic tripod head to get parallax-free panoramic imagery
- *Use the right mode:* Black-and-white is best for tracing detail but colour is good for recording material type and pigment.
- Use RAW or 'high quality' and 'high sensitivity' setting on digital cameras.
- Geotag the images.

III The 3 Procedural Rules

3.1 Record Photo Layout

Make witnessing diagrams of:
- The ground plan with the direction of north indicated.
- *The elevations of each facade (at an appropriate scale 1:*50, 1:100 - 1:500).
- Photo locations and directions (with frame numbers).
- Single photo coverage and stereo coverage.
- Control point locations, distances and plumb-lines.
- If using 'natural' points a clear diagram showing each point is required.

3.2 Log the Metadata

Include the following:
- Site name, location and geo-reference, owner's name and address.
- Date, weather and personnel. Client, commissioning body, artists, architects, permissions, obligations, etc.
- Cameras and optics, focus and distance settings.
- Calibration report, including the geometric and radiometric results if available.
- Description of place, site, history, bibliography etc.

Remember to document the process as you go.

3.3 Archive

Data must be complete, stable, safe and accessible:
- Check completeness and correctness before leaving the site.
- Save images to a reliable location off the camera. Save RAW formats and TIFF copies.
- Remember a DVD is not forever!
- Write down everything immediately.
- The original negatives/diapositives/RAW files are archive documents. Treat and keep them carefully.
- Don't cut into the format if cutting the original film. If using digital cameras, don't crop any of the images and use the full format.
- Ensure the original and copies of the control data, site diagrams and images are kept together, as a set, at separate sites on different media.

POST-PROCESSING OF PHOTOGRAPHS

- Choosing File Format/Image Compression

As mentioned, shooting is advised with RAW file format and at highest available resolution. Conversion of RAW files into **lossless, uncompressed format**, such as TIFF, is the most advisable way if very high resolution is required. In more flexible circumstances, conversion with **high quality compression** to JPEGs file format is the standard option.

- Converting RAW files into other image file formats

The conversion can be made with various ways: one option is using proprietary image-editing software targeted for RAW file conversion support, such as Adobe Photoshop. Software specifically targeted for this reason are also provided by camera manufacturers. Finally, freeware and open source alternatives are also an option and one can find such services online. Common editing decisions during conversion involve **colour balance, white balance, exposure values, sharpening and noise reduction, as well as conversion format & resolution.**

- Distortion Correction

Modern RAW processing software often has the ability to perform **lens correction using pre-calibrated parameters** for a broad range of camera and lens combinations. Examples include Adobe Camera RAW (ACR), Lightroom, Aperture, DxO Optics and PTLens. If images have received this preparation step, the interior parameters should later be set accordingly for the bundle adjustment in the photogrammetric software.

- Geometric transformations

No manual alterations should be made on the original image size or other geometrical transformations such as rotating, scaling, stretching, etc.

- Masking

"Masking" serves to block off portions of an image or images that should not be included in photo alignment or texture generation. This process can be done in **with specific tools in image-editing software** and greatly facilitated by the correct choice of background. Some **photogrammetric software** such as Photoscan can also support masking of photos.

Green Screen / Chroma Key

If using the "green screen" method, in order to automatically remove background and produce masks of the object, specific software termed under "Chroma Key" can be used, either as stand-alone software or as plug-ins for image editors (also available as free-to-use software).

- Radiometric corrections

Radiometric modifications cannot affect the reconstruction results. Nonetheless, excessive histogram alterations on the photos are not advised, if made with an approach of "maximum visual appeal". If there is indeed need for amendments on the photos (i.e. in order to reveal over/underexposed details), such as **white balance corrections**, **contrast stretching**, **noise removal**, etc., the best option is to use photography-editing software (such as Adobe Lightroom), which can impose these modifications and store them separately from the image file, thus maintaining the **original information**. Software such as this can also apply the same **modification set on grouped images**, thus sustaining uniformity.

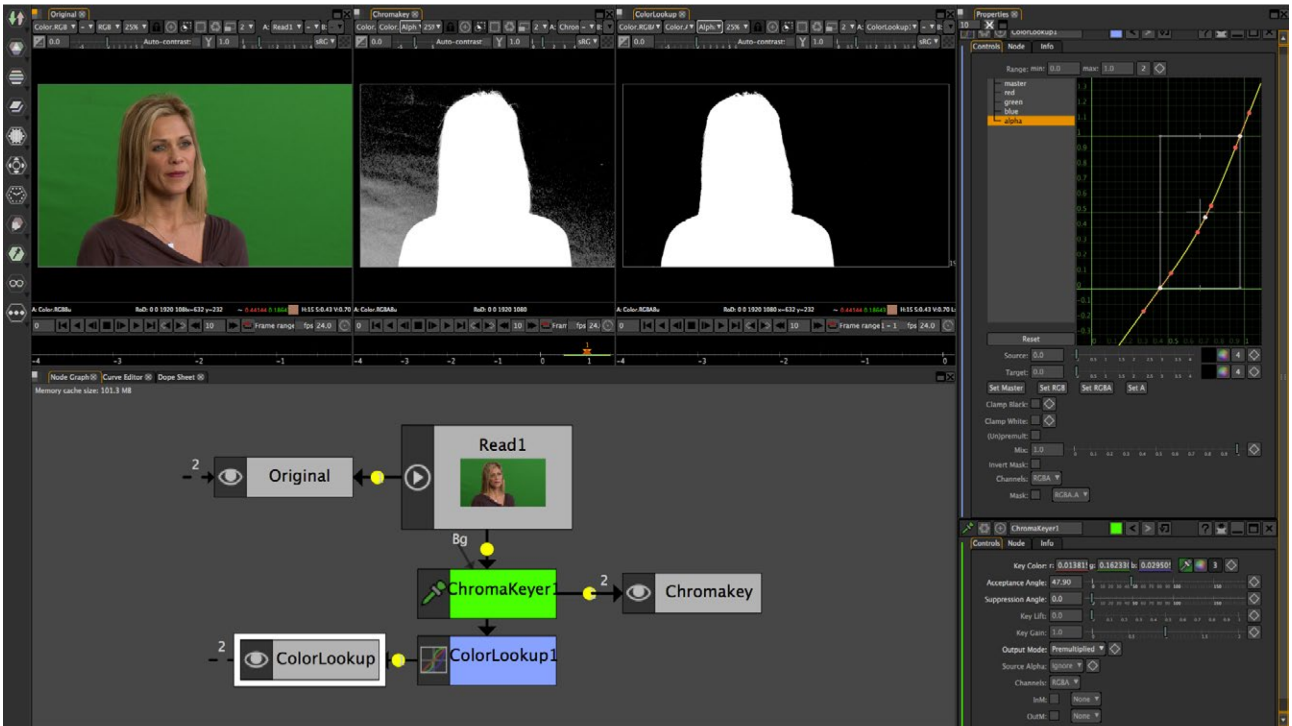
- Archiving, Evaluating, Filtering

Photographic-image software is also a great asset for management of large photographic archives. **Grouping, storing, filtering** and accessing of photos can be made faster and more refined. Inspection and **attribution of metadata (EXIF)** is another important service. Finally, evaluation of the photos and removal of unsuitable (blurred or unfocused ones) is the last step before input in the photogrammetric software.

** Recommended Open Source Image Editing Software:*

GIMP – The GNU Image Manipulation Program: free software package for use with Windows, Apple and Linux operating systems. (http://www.gimp.org)

Example of Lens Correction/Distortion Removal[15]



Chroma Key software: Automated generation of masks based on colour range[16].

15 Screenshots from DxO Optics Software: http://www.dxo.com/us/photography/photo-software/dxo-viewpoint/features#3293
16 https://colorgrade13.wordpress.com/

V. CAMERA CALIBRATION

Explicit knowledge of interior orientation parameters of the camera are not necessary in automated approach, since their calculation can be integrated in the bundle adjustment process. Initially, **generic** values for the parameters are employed, which are based on the knowledge of the camera and lens type combination. After the alignment process has been completed these values become further **refined**. It is obvious that **more accurate preliminary values, will assist to a more accurate bundle adjustment**. Therefore, acquiring the information of the interior orientation parameters of the camera by means of a camera calibration process in advance is advised in cases of high accuracy requirements.

Generic Values from EXIF metadata

Information about the camera & lens used to capture each image is recorded in the EXIF metadata of the image file format by the camera firmware. Photogrammetric software can draw information from the EXIF metadata to set the generic initial values.

For example, the following information can be derived by the photogrammetric software from the EXIF metadata:

- *Camera type:*

[Frame | Spherical | Fish-eye] The camera type determines the appropriate projection method.

- *Physical Pixel size and ratio:*

These are calculated based on the camera’s frame size and the pixel-matrix size (resolution).

- *Focal Length:*

Focal length of lens is calculated in pixels based on physical pixel size.

** Please note that if EXIF data is missing or incomplete, these parameters should be manually provided by the user. The camera data can be found in the full specification list of the product, as provided by the manufacturer.*

Calculated, Camera & focal length specific Values

Non-generic, accurate camera calibration data can be used in order to optimize alignment, as stated. An easy way to acquire these is by means of a camera calibration software. An easy way is using software that uses a pattern/chessboard projection on the LCD screen as calibration target.

- *Commercial Software:*

Agisoft Lens	CamCal
Australis	iWitness
Photomodeler	Camera Calibrator
3DM CalibCam	LISA-FOTO

- *Open Source Camera Calibration Toolboxes:*

Fauccal - Fully Automatic Camera Calibration, by NTUA, for Matlab
http://portal.survey.ntua.gr/main/labs/photo/staff/gkarras/fauccal.html
http://photogram.tg.teiath.gr/?page_id=56
Camera Calibration Toolbox for Matlab by Jean-Yves Bouguet
http://www.vision.caltech.edu/bouguetj/calib_doc/

Camera calibration parameters are not uniform across platforms, neither are the models by which camera calibration is performed - for this reason exchange of parameters between different calibration software or between calibration and photogrammetric software can lead to inconsistency and conversion for communication purposes might be needed. Open software such as CamCal[17] offer full documentation of the model and algorithms used, as opposed to proprietary software.

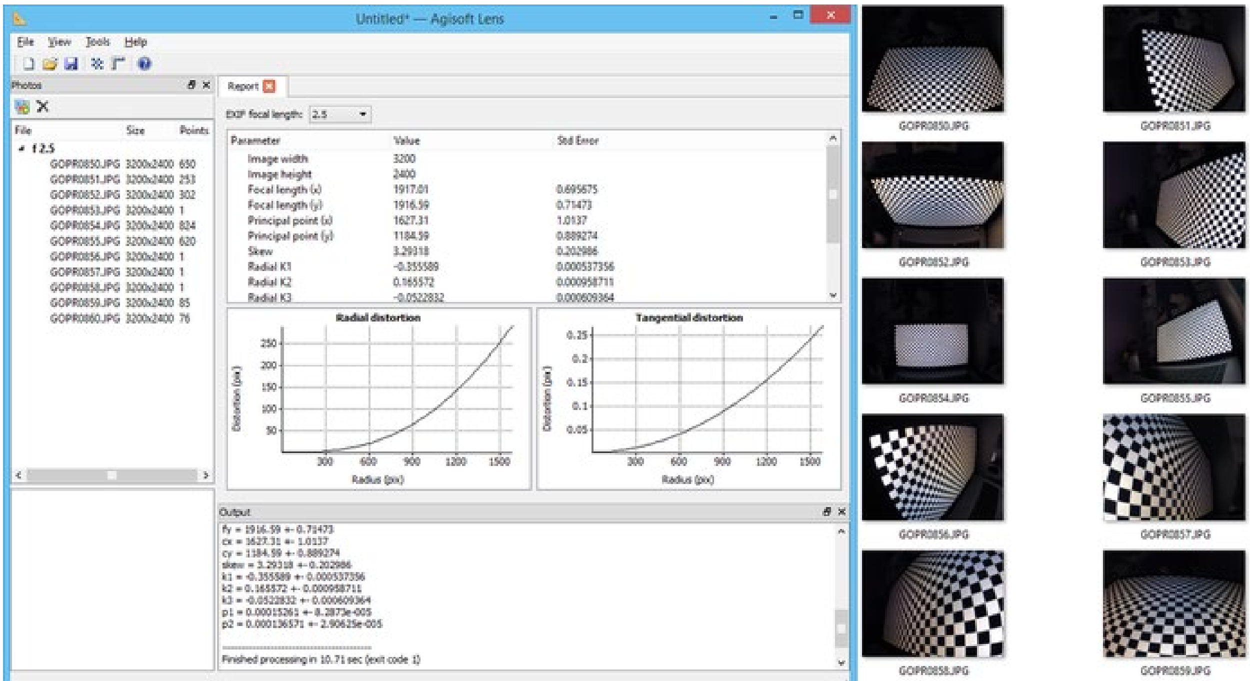
17 Jean-Philippe Tarel, Jean-Marc Vezien. Camcal v1.0 Manual A Complete Software Solution for Camera Calibration. [Technical Report] RT-0196, 1996, pp.19.

Camera calibration parameters[18]:

fx, fy	Focal length in x- and y-dimensions measured in pixels (based on pixel size).
cx, cy	Principal point coordinates, i.e. coordinates of lens optical axis projection on sensor plane.**
skew	Skew coefficient between x & y axis.
k1, k2, k3, k4	Radial distortion coefficients*.
p1, p2	Tangential distortion coefficients.

** using Brown model. Fish eyes and ultrawide angle lenses are poorly modeled by the Brown distortion model, which explains why they are not advised.*
*** The image coordinate system has the origin at the top left image pixel, with the center of the top left pixel having coordinates (0.5, 0.5). The X axis in the image coordinate system points to the right, Y axis points down.*

Camera Calibration Software using projection pattern on LCD screen as calibration target



Screenshot from a digital camera calibration process:[19]

Input images, the list of interior orientation parameters and the plots of radial and tangential distortion.

** Please note that when calibration is focal length specific - if using variable focal length lens, calibrate at each length used.*
** Also, please note that camera calibration is also depended on focusing distance. Therefore, keeping focusing distance stable is also advised.*

18 Based on Agisoft's calibration software "Lens" which has interoperability with its photogrammetric software "Photoscan".
19 http://robo-tech.weebly.com/1/post/2014/04/go-pro-2-lens-calibration.html

VI. DATA PROCESSING

CHOOSING PHOTOGRAMMETRIC SOFTWARE

Availability/Terms of use

For the scope of our investigation, an important categorization factor is availability/distribution license/terms of use of the photogrammetric software. Software can be categorised according to end-user license agreements, with which they are distributed. This ranges from:
- commercial software, which has a monetary price and undisclosed source code,
- proprietary but free to use, which is given for public use under specific conditions, but likewise with undisclosed source
- free & open source, under a variety of licenses[20], which is available to all for use, editing and distributing.

** In the case of free to use software, one must pay careful attention to the possibility of automatic copyright transfer included in the Terms of Use of some (often cloud-based) photogrammetry software programs. For example, services like 123dCatch should be avoided when digitizing specimens owned by third parties or when rights of use of the models need to be privately owned.*
** Likewise, in the case of open source software, one must be careful about the restrictions passed on the output files. This most notably has to do with their non-commercial character. For example, VisualSFM is free for personal, non-profit or academic use.*

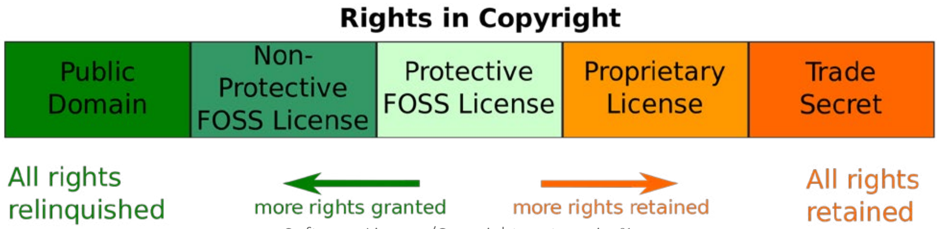
Free Software	Proprietary Software
Public Domain Software (with source)	Public Domain Software (without source)
Software under various permissive licenses	Shareware
Copylefted Software (Software under GPL)	

Nowadays, the **FOSS** (Free and Open Source Software) tools are on par or exceed their commercial brethren. If supported by an active community for troubleshooting and information exchange, FOSS offer a valuable asset with a democratic and open approach.
It should be noted that this refers to the automated approach using Structure from motion & Multi-view Stereo algorithms.

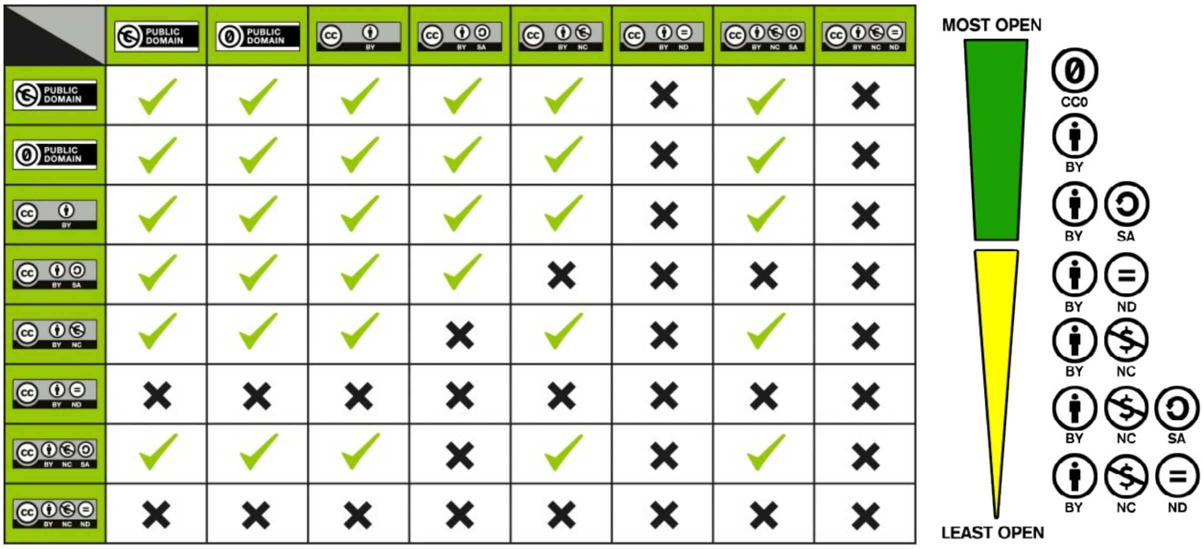
Another alternative is the use of **web services**. In web services, the process takes place not using the actual local computer resources but treats it as a client and uses a remote server network for the calculations. Their black box nature and little to no control over the 3D reconstruction or manipulation of the results are important & practical drawbacks. Nonetheless, they are a frequent occurrence.The reasons of these can be speculated:
- High computational power is needed for bundle adjustment. Remote computation in servers can offer significant processing strength over individual personal computers.
- Since this area is under rapid development, the software hosted by the servers is possibly objected to constant revisions/updates.
- Since these web services are targeted mainly to untrained users and given the relative complexity of the process, there is a presumption that interfering with parameters is best avoided.

Thus, for an adequate outcome, all weight is put on providing guidelines and support for better input preparation on behalf of the users & investing in a strong development team working on the technical details.

20 Such as creative commons (http://creativecommons.org/), GNU General Public License, etc.



Software License/Copyrights categories[21]



Creative Commons License Compatibility Chart & Legend[22]

COMPUTER REQUIREMENTS

Apart from a strong, multi-threaded processing set-up, other important computing parameters include amplitude of RAM, as well as the employment of any available GPUs. If a GPU-supporting graphics card is installed, it is advisable to exchange CPU with GPU processing power on a 1 : 1 core ratio.

Recommended Configurations

Configuration	Basic	Advanced
CPU	Quad-core Intel Core i7 CPU	Six-core Intel Core i7 CPU
RAM	16GB or 32 GB DDR3	32GB or 64GB DDR4/DDR3
GPU	Nvidia GeForce GTX 780	Nvidia GeForce GTX 780

CPU vs GPU computational strength[23]

21 https://en.wikipedia.org/wiki/Software_license
22 https://wiki.creativecommons.org/index.php/Frequently_Asked_Questions
23 For more information, visit: http://www.nvidia.com/object/what-is-gpu-computing.html

LIST OF PHOTOGRAMMETRIC SOFTWARE

The following table presents some of the most commonly used software[24].

Commercial Software		
Software	Provider	Web-Link
Photoscan	Agisoft	www.agisoft.com/
Photomodeller	Eos Systems Inc.	http://www.photomodeler.com/index.html
ReCap	Autodesk	https://recap.autodesk.com/
ContextCapture	Acute3D/Bentley Systems	www.acute3d.com/
3DF Samantha	3Dflow	www.3dflow.net/
Pix4Dmapper	Pix4D	https://www.pix4d.com/
Australis	Photometrix	www.iwitnessphoto.com/
iWitness	Photometrix	http://www.photometrix.com.au/australis/
Aspect3D	ArcTron Excavation GmbH	aspect3d.arctron.de/
Pix4Dmapper	Pix4D	pix4d.com/
3dsom	3dsom	http://www.3dsom.com/
Software 4E	4E	http://4-e.es/
Elcovision 10	PMS AG	wvw.elcovision.com/
Enwaii	Banzai Pipeline	www.banzai-pipeline.com/home.html
Photosculpt	Hippolyte Mounier	photosculpt.net/
PhotoSketch (SketchUp plugin)	Brainstorm Technology	www.brainstormllc.com/
ScannerKiller	XYZRGB	www.xyzrgb.com/#!scannerkiller/cvzb
Vi3Dim	Vi3Dim	http://www.vi3dim.com/#!about1/cmh7

Open Source Software	
VisualSFM: A Visual Structure from Motion System, by Chang-chang Wu	http://ccwu.me/vsfm/
Bundler - Structure from Motion for Unordered Photo Collections by Noah Snavely	http://www.cs.cornell.edu/~snavely/bundler/
MicMac, a SFM open-source code released by the Institut Géographique National (FR)	www.micmac.ign.fr
SURE	http://www.ifp.uni-stuttgart.de/publications/software/sure/index.en.html
PMVS-CMVS	wvw.di.ens.fr/pmvs/
E-foto	www.efoto.eng.uerj.br/en
OpenMVG	http://imagine.enpc.fr/~moulonp/openMVG/
CMPMVS	http://ptak.felk.cvut.cz/sfmservice/websfm.pl?menu=cmpmvs
PPT	184.106.205.13/arcteam/ppt.php
Palentier	http://palentier.com/
Insight 3.0	insight3d.sourceforge.net/

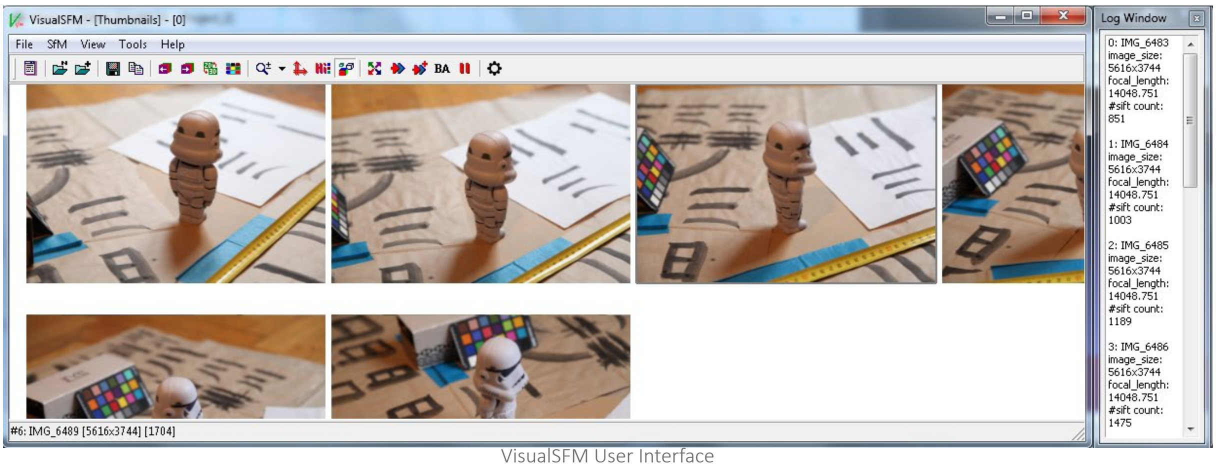
Web-Based / Online Services	Website
123DCatch	www.123dapp.com/catch

24 For a comprehensive contemporary list please see the following:
https://en.wikipedia.org/wiki/Comparison_of_photogrammetry_software
Bartos, K. et al, "Overview of Available Open-Source Photogrammetric Software, its Use and Analysis ", IJIER, Vol. 2-04, 2014

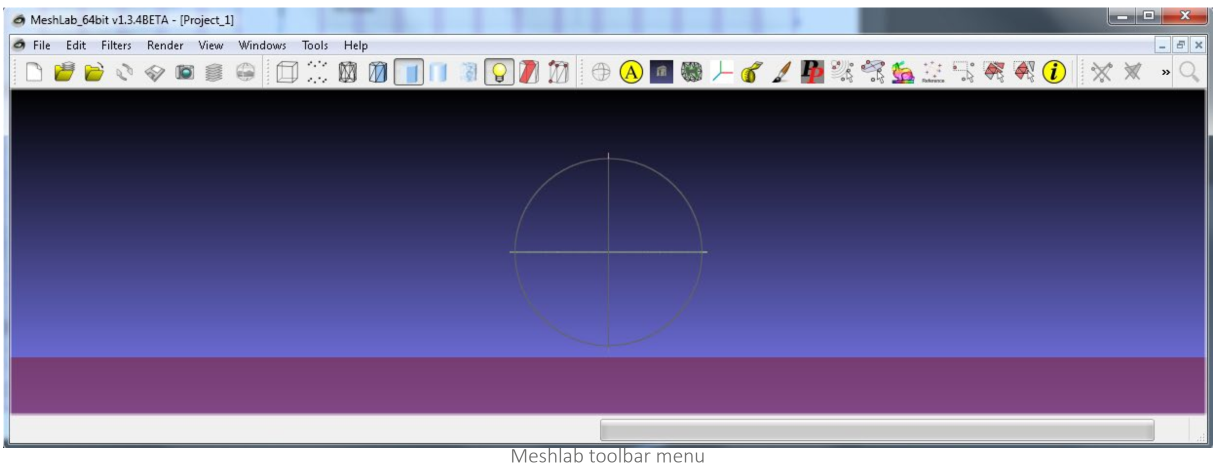
ARC 3D	www.arc3d.be/
Memento	memento.autodesk.com/about
Photosynth	photosynth.net/
PHOV	www.phov.eu/
WEBDLT	dlt.fmt.bme.hu/
CMP Sfm Web Service	ptak.felk.cvut.cz/sfmservice/websfm.pl?menu=webservice
PhotoModel3D	www.visualsize.com/
MetrologyEngine	dragonox.cs.ucsb.edu/MetrologyEngine/
VideoTrace	punchcard.com.au/wordpress/

For users more familiar with computer technology, toolboxes for various languages/environments are also available:

Open Source Toolboxes	
FIT3D - Matlab Toolbox by I. Esteban	http://www.fit3d.info/?page_id=8
SfM toolbox for Matlab by V. Rabaud	http://vision.ucsd.edu/~vrabaud/
Matlab Functions for Multiple View Geometry by A. Zissermann	http://www.robots.ox.ac.uk/~vgg/hzbook/code/
Structure and Motion Toolkit for Matlab by Phil Torr	http://www.mathworks.com/matlabcentral/fileexchange/4576-structure-and-motion-toolkit-in-matlab
Python Photogrammetry Toolbox GUI by Pierre Moulon and Arc-Team	http://184.106.205.13/arcteam/ppt.php
Open Source Photogrammetric Toolbox for Matlab, by Laboratory of Photogrammetry of the Department of Surveying Engineering, TEI Athens	http://photogram.tg.teiath.gr/?page_id=122



VisualSFM User Interface



Meshlab toolbar menu

AUTOMATED PROCESS OVERVIEW

As stated, this handbook will give focus on the “Computer Vision” approach, since it is deemed by far the most user friendly and in active development for the future. For this reason, only the automated approach will be presented in detail step by step. An example application will be used as visual support for this purpose.

Example Application Project Planning

Object

*Physical Dimensions (Height*Width*Depth)*	
Texture Properties	*13cm X 3cm X 3cm*
Smooth, Low Texture, Non-glossy/Diffuse Surface, No self-Occlusion, Shallow Surface Profile	
Smallest Feature Size	*0.1mm (mould joint)*

Equipment

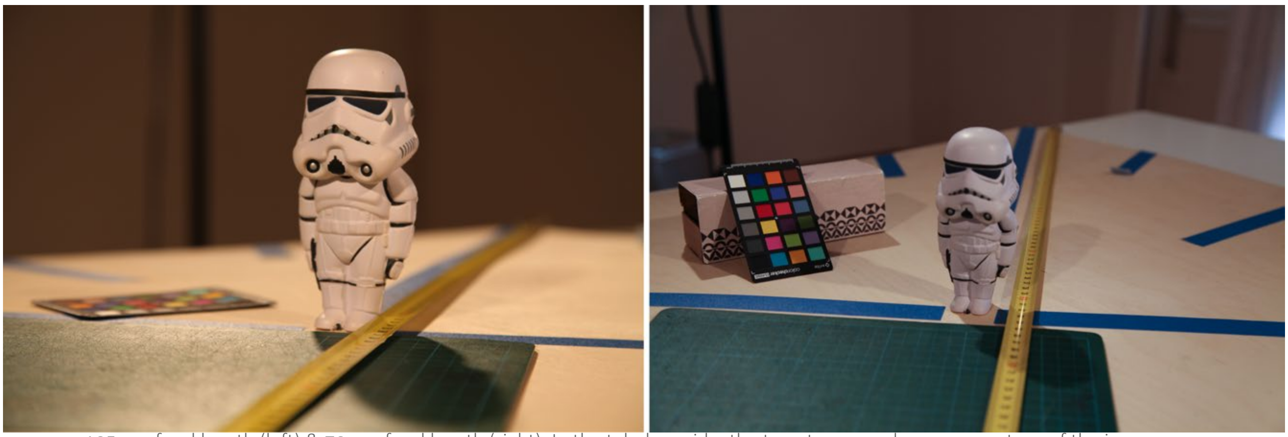
Camera: Canon EOS 5D Mark II

Sensor size:	*36.00mm x 24.00mm*
Image Format & Resolution	*RAW: 21.0 Megapixels / 25.8 MB & high quality JPGs: 5616 x 3744 resolution/~6.1MB*
Pixel size	*0.0064mm*

Lens: Canon Zoom Lens 24-105mm

Used Focal Length	*105mm*
Angle of View	*23° 20’*
*Focus Distance**	*~0.70cm*

The following combination was chosen to achieve maximum coverage of the object on the sensor frame at minimum shooting distance, thus leading to the tele-lens side of the spectrum, although the wider angle side would lead to more helpful perspective distortions for the bundle adjustment step.



105mm focal length (left) & 70mm focal length (right). In the tele-lens side, the target covers a larger percentage of the image area.

Level Of Detail

Ground Sampling Distance	*[Pixel Size*Focus Distance/Focal Length] 0.0064mm*700mm/105mm GSD=0.042mm*
Accuracy	*GSD*2=0.085mm*
Evaluation	*Smallest Feature > Accuracy = TRUE*

Shooting Settings

Aperture	*f/5.6 (for larger depth of field)*
ISO	*250 (for low grain > compensate with lighting)*
Shutter Speed	*~1/100*
Metering	*Pattern*
White Balance	*Auto*

Photographs

Approved/Shot: 73/132
Categorized in 3 Image Sets for multiple, step-by-step photogrammetric trials:

25 photos	*only 5 stars rated*
50 photos	*3 stars and above*
73	*all photos*
Rotational Angle	*~ 20°*
Shooting Heights	*3*
Overlaps	*~80%*

Photo Shooting Software

- Canon EOS Utility 2

Raster Graphics Editing Software

- Adobe Lightroom (RAW conversion, corrections & file management)
- Adobe Photoshop (masking)

Photogrammetric Software

- Agisoft Photoscan 1.2.0 build 2127[25]

Mesh editing Software

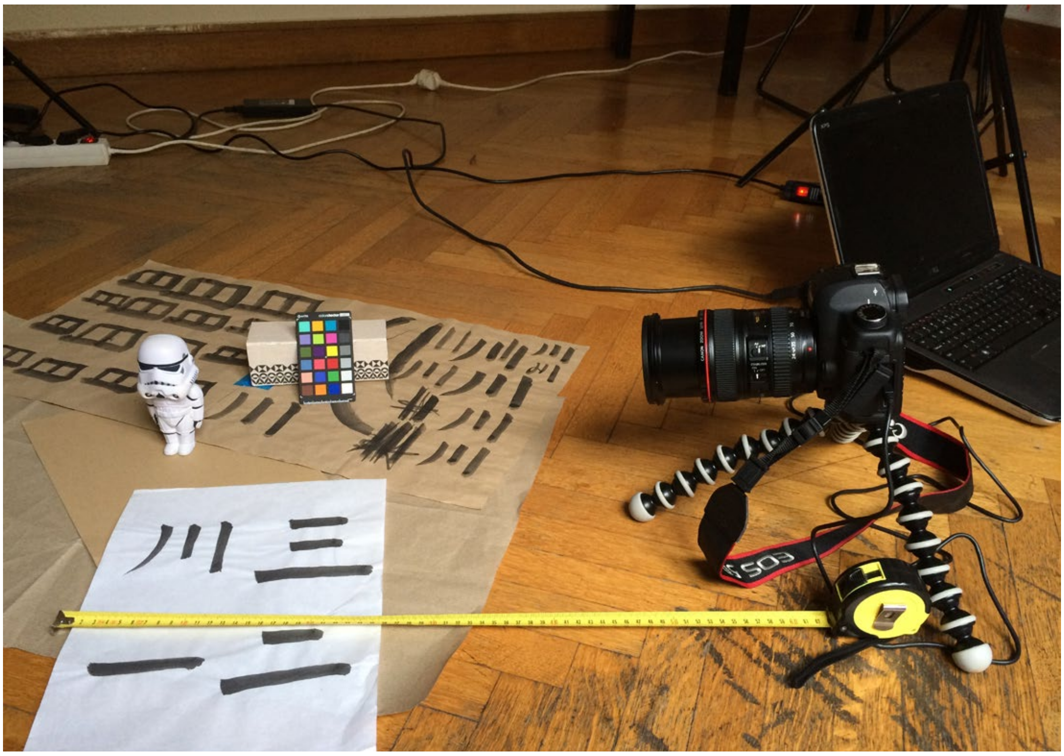
- MeshLab

Computer Specifications

CPU	*Intel Core i7 @2.67Ghz (max. @2.79Ghz)*
RAM	*16GB DDR3*
GPU	*NVIDIA GeForce GTX 460 with 1GB (GPU support)*

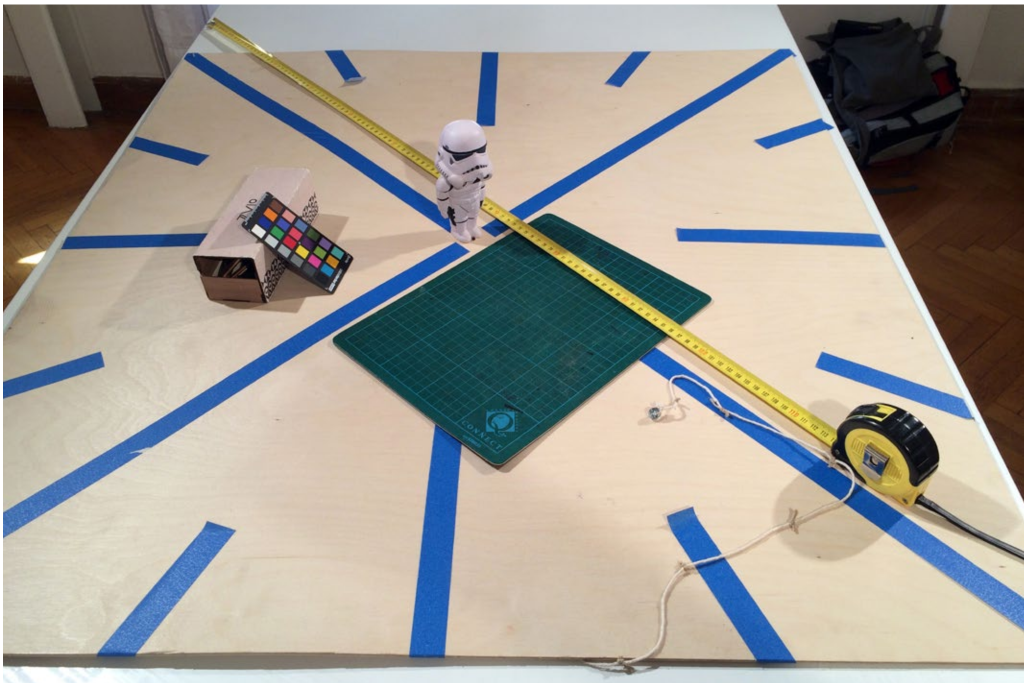
25 http://www.agisoft.com/

Photographic Set-Up of Example Application



DSLR Canon EOS 5D - Mark II with Canon Zoom Lens 24-105mm, set at 105mm focal length
Connected via USB with Laptop
with Canon Utility Software for Remote Shutter Release and Live Viewing Screen
Color Card for White Balance
Measuring Tape for Scale Reference
Background with variable pattern

Construction of photo-shooting "platform"



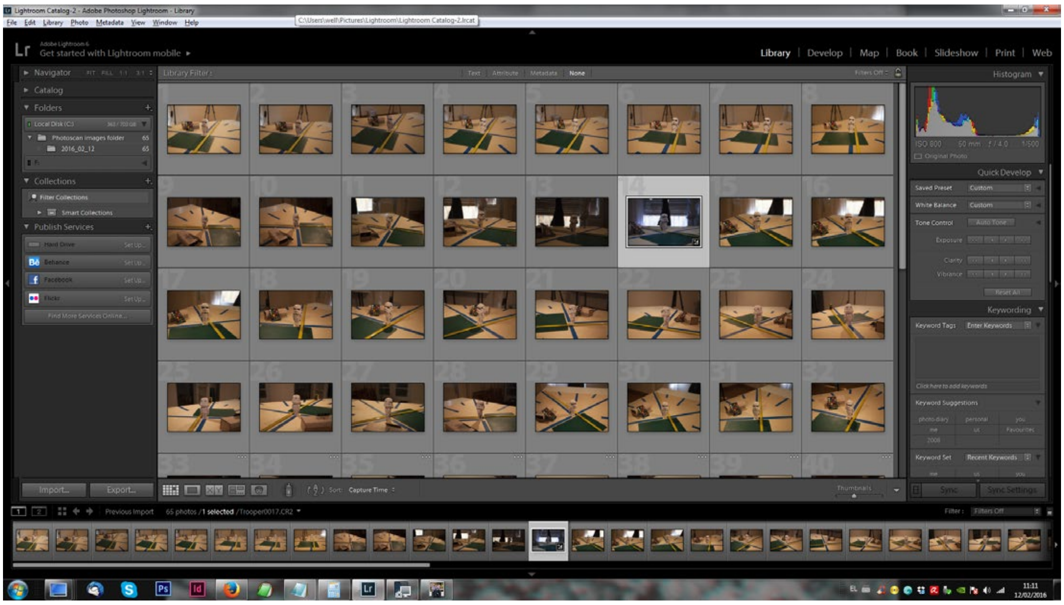
Makeshift Platform for better rotation control/angle measurement of camera positions

3 Lights set-up with dimmer control at triangle formation and intensity/direction for shadow control

Movable Platform for the Camera Rig

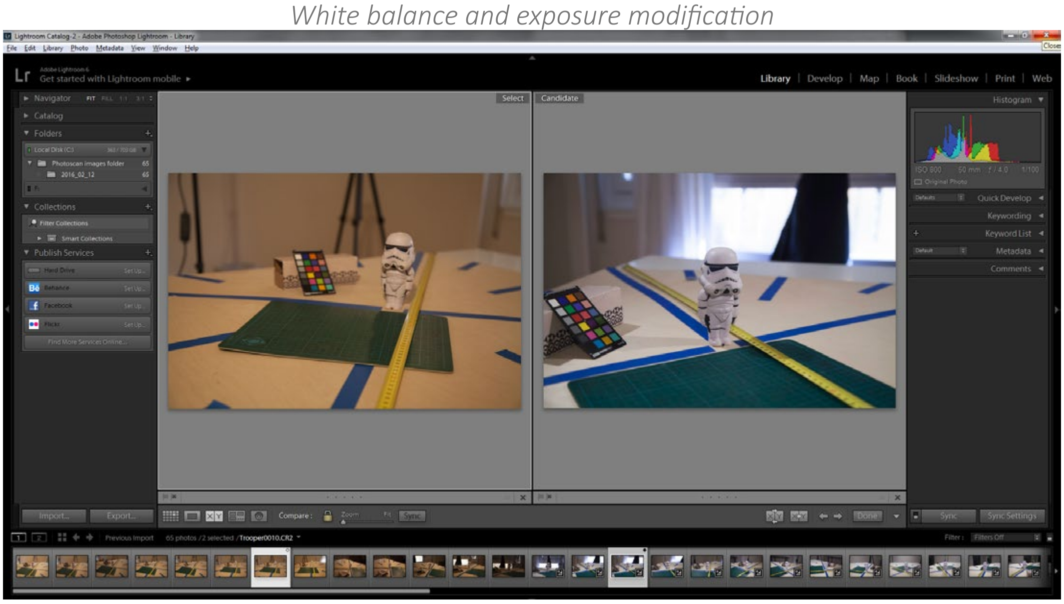
Platform in action with tripod

Management of Image Files



Loading of photographs in Adobe Lightroom

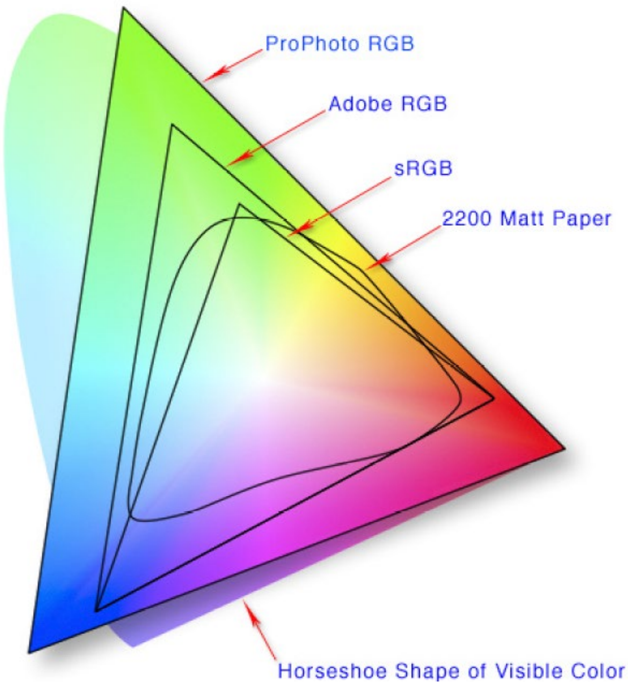
White balance and exposure modification



Uniform application of modification presets on image set/Manual adjustments for Sharpen & Noise Reduction

Visual Evaluation of Photos at 1:1 Scale: Flagging Rejected and Rating Approved (1-5 stars scale)

> Conversion of RAW files to images in jpg format with 300 dpi resolution and maximum quality compression in prophoto RGB color space



Prophoto Colour Space is larger than commonly used sRGB and can provide more detailed colour information

Note:
1) The exported images from Adobe Lightroom, that had gone through RAW conversion, contrast stretching and white balance correction (with small amounts of noise reduction and sharpening) were compared with the original JPGs that were simultaneously shot by the camera. The results of bundle adjustment in terms of tie points and reprojection error were similar.
2) sRGB and ProPhoto colour spaces were compared with the same image set: ProPhoto yielded slightly better results.

Trials

Trials were conducted with all three sets of images. The process was completed with the largest set.

- *1st Set:* [25 images]

Not enough coverage of the object was achieved, yielding to unsuccessful alignment of cameras, as well as an incomplete sparse cloud.

Rejected, unaligned images

- *2nd Set:* [50 images]

Some unaligned cameras from a specific viewing angle leading to incomplete coverage.

Rejected, incomplete coverage.

- *3rd Set:* [73 images]

This set was fully successful and used for the completion of the project.

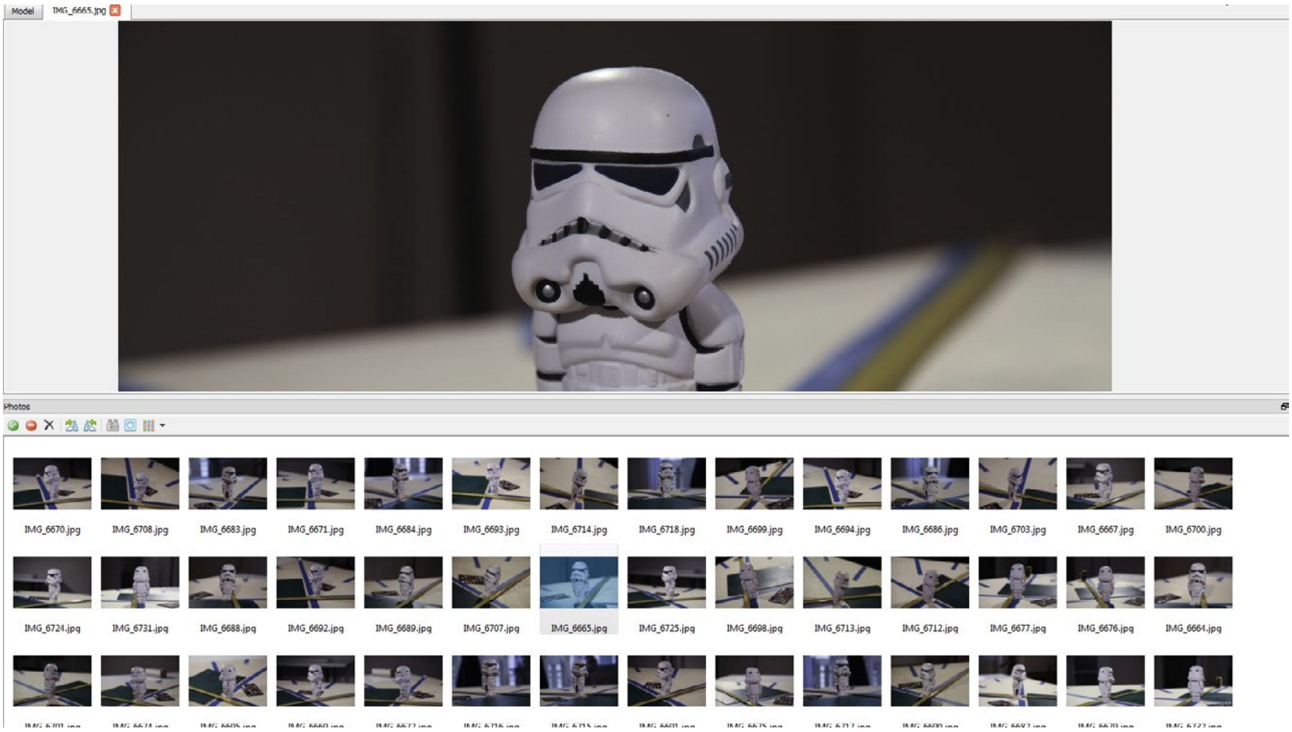
Successful

Walkthrough

In summary:

1. Loading & assessing of photographs
2. Camera alignment & sparse point cloud generation
3. Tie point cloud filtering & camera optimization
4. Dense point cloud generation
5. Mesh generation
6. Texture generation
7. Georeferencing
8. Data export

I. Loading and assessing photographs



Loaded Images

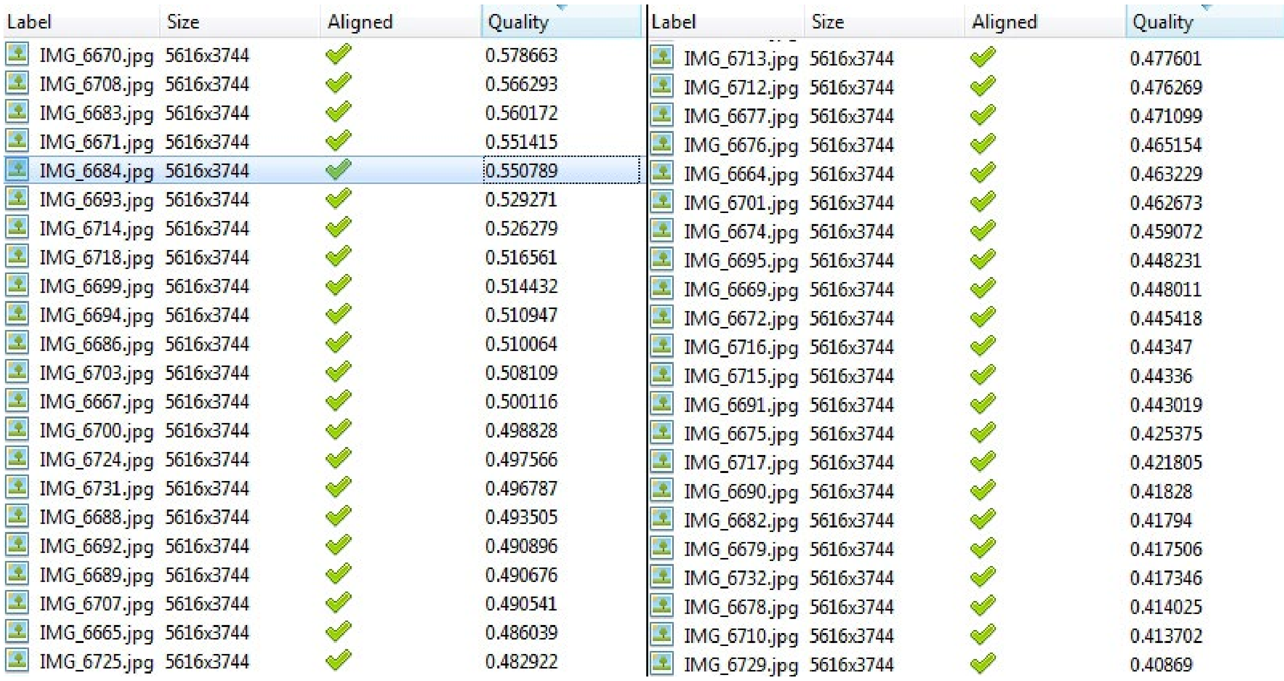
Supported Image file formats:

JPEG (Joint Photographic Experts Group)	.jpg / .jpeg
Tiff (Tagged Image File Format)	.tiff / .tif
Portable Network Graphics	.png

Microsoft Windows Bitmap	.bmp
OpenEXR (for HDR images)	.exr
Portable Bitmap (for UNIX OS)	.ppm / .pgm
JPEG Multi-picture Object (for stereo image pairs)	.mpo
Norpix Sequence File (for image sequences from video)	.seq

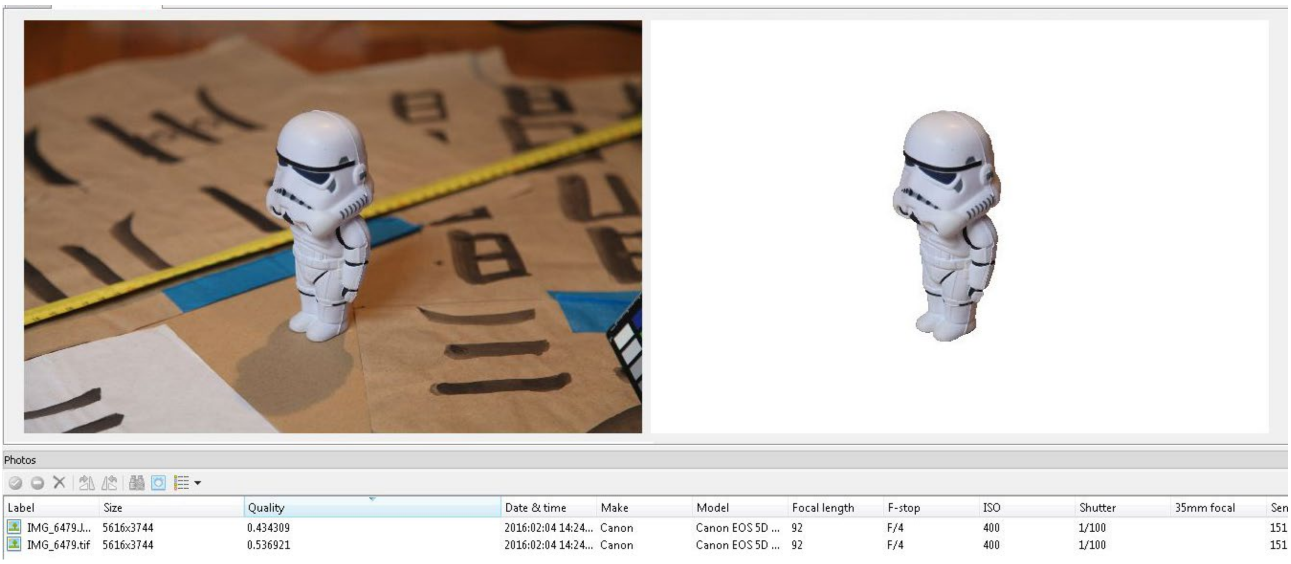
Automated Image Quality Estimation

Some software offer automated image quality estimation, which is based on analysis of the sharpness level of most focused areas of each photograph. Photographs with lower score than acceptable are recommended to be disabled for higher accuracy.



Label	Size	Aligned	Quality	Label	Size	Aligned	Quality
IMG_6670.jpg	5616x3744	✓	0.578663	IMG_6713.jpg	5616x3744	✓	0.477601
IMG_6708.jpg	5616x3744	✓	0.566293	IMG_6712.jpg	5616x3744	✓	0.476269
IMG_6683.jpg	5616x3744	✓	0.560172	IMG_6677.jpg	5616x3744	✓	0.471099
IMG_6671.jpg	5616x3744	✓	0.551415	IMG_6676.jpg	5616x3744	✓	0.465154
IMG_6684.jpg	5616x3744	✓	0.550789	IMG_6664.jpg	5616x3744	✓	0.463229
IMG_6693.jpg	5616x3744	✓	0.529271	IMG_6701.jpg	5616x3744	✓	0.462673
IMG_6714.jpg	5616x3744	✓	0.526279	IMG_6674.jpg	5616x3744	✓	0.459072
IMG_6718.jpg	5616x3744	✓	0.516561	IMG_6695.jpg	5616x3744	✓	0.448231
IMG_6699.jpg	5616x3744	✓	0.514432	IMG_6669.jpg	5616x3744	✓	0.448011
IMG_6694.jpg	5616x3744	✓	0.510947	IMG_6672.jpg	5616x3744	✓	0.445418
IMG_6686.jpg	5616x3744	✓	0.510064	IMG_6716.jpg	5616x3744	✓	0.44347
IMG_6703.jpg	5616x3744	✓	0.508109	IMG_6715.jpg	5616x3744	✓	0.44336
IMG_6667.jpg	5616x3744	✓	0.500116	IMG_6691.jpg	5616x3744	✓	0.443019
IMG_6700.jpg	5616x3744	✓	0.498828	IMG_6675.jpg	5616x3744	✓	0.425375
IMG_6724.jpg	5616x3744	✓	0.497566	IMG_6717.jpg	5616x3744	✓	0.421805
IMG_6731.jpg	5616x3744	✓	0.496787	IMG_6690.jpg	5616x3744	✓	0.41828
IMG_6688.jpg	5616x3744	✓	0.493505	IMG_6682.jpg	5616x3744	✓	0.41794
IMG_6692.jpg	5616x3744	✓	0.490896	IMG_6679.jpg	5616x3744	✓	0.417506
IMG_6689.jpg	5616x3744	✓	0.490676	IMG_6732.jpg	5616x3744	✓	0.417346
IMG_6707.jpg	5616x3744	✓	0.490541	IMG_6678.jpg	5616x3744	✓	0.414025
IMG_6665.jpg	5616x3744	✓	0.486039	IMG_6710.jpg	5616x3744	✓	0.413702
IMG_6725.jpg	5616x3744	✓	0.482922	IMG_6729.jpg	5616x3744	✓	0.40869

Image Quality Estimation of used Photographs: The estimation results are medium in average.



Label	Size	Quality	Date & time	Make	Model	Focal length	F-stop	ISO	Shutter	35mm focal	Sen
IMG_6479.J...	5616x3744	0.434309	2016:02:04 14:24...	Canon	Canon EOS 5D ...	92	F/4	400	1/100		151
IMG_6479.tif	5616x3744	0.536921	2016:02:04 14:24...	Canon	Canon EOS 5D ...	92	F/4	400	1/100		151

Masking Photos will remove blurred background on photographs with shallow DoF and increase quality estimation

Organising Camera Groups (Stations)

Photographs from a single camera station -or from locations with negligible distance relative to camera-target distance- should be placed in a single camera group. At least two stations are needed for the alignment of the cameras (with a single station, only photographic panoramas can be created).

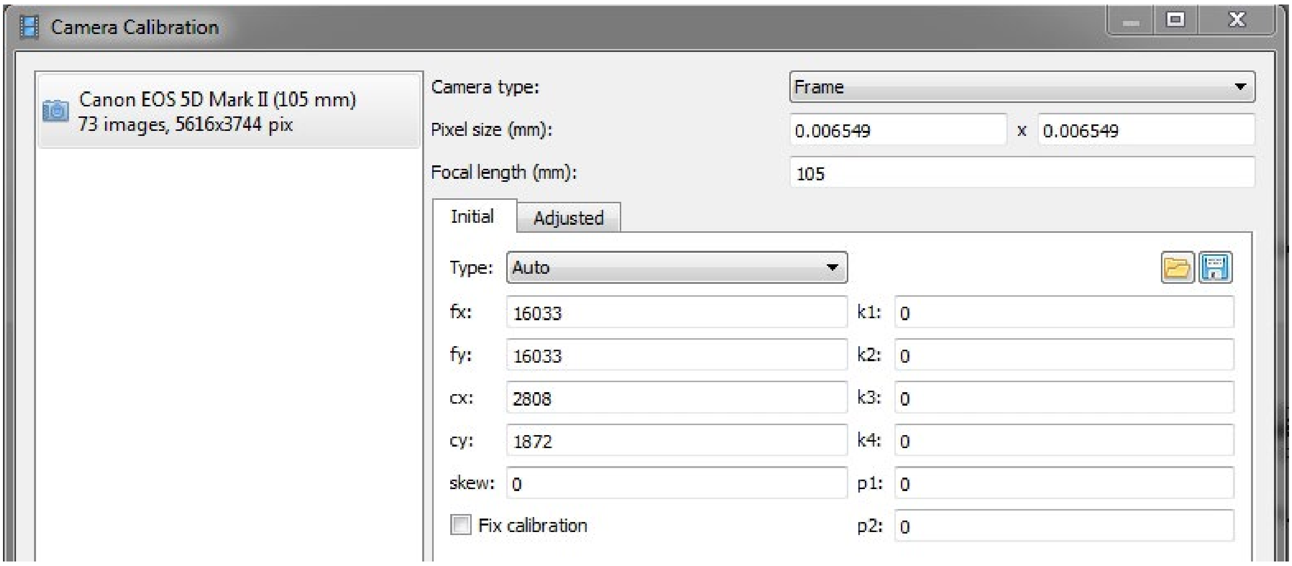
Initial Camera Interior Orientation Parameters

As stated in the camera calibration chapter, automated initial values are used, based on the information provided by the EXIF data.

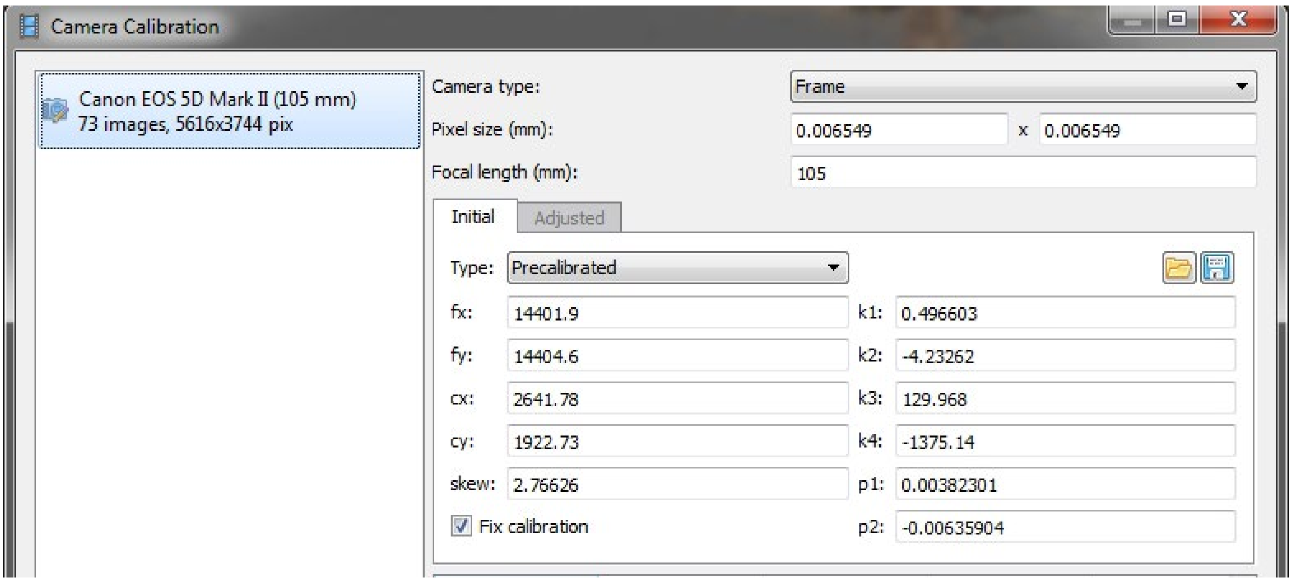
Reminders:

- If no EXIF data is available, manual input is mandatory.
- If camera calibration data is available, please load at this stage and request that camera parameters remain fixed during camera alignment step.
- If photos have received distortion removal, keep all coefficients fixed at zero apart from principal point distance and projection of optical axis.

Option 1) Initial Camera Parameters for Canon EOS 5D Mark II & 24-105mm Lens



Option 2) Precalibrated Camera Parameters for Canon EOS 5D Mark II & 24-105mm Lens



** A trial with precalibrated data of the same camera-lens configuration was used. The calibration data was computed by Agisoft's Lens software and exported in xml file format. The alignment results judging from tie point cloud and reprojection error were similar (13.073 tie points found, maximum reprojection error 0.9). The process was completed with automatic initial values.*

II. Alignment of cameras & Sparse Point Cloud Generation

Image analysis, **interior orientation** (refinement of camera parameters) and **relative orientation** are processed simultaneously at the camera/bundle/photograph **alignment stage**.

Image analysis involves **feature detection**, **feature matching** and **generation of sparse point cloud** of the **found matches/tie points**.

The following parameters define the parameters of the algorithms involved:

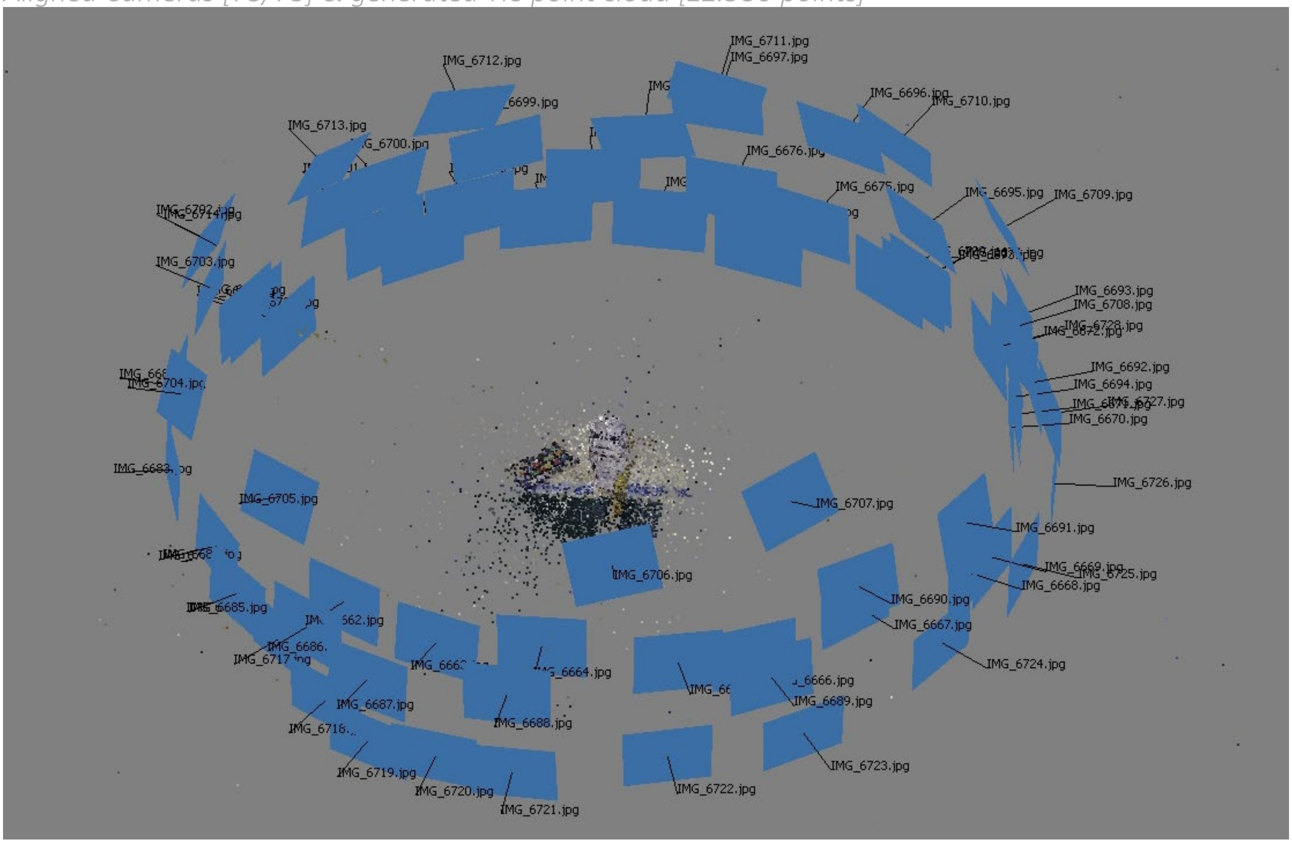
1. *Accuracy level:* Defines the **resolution/size of the images** to be processed. Highest setting will use the original resolution, whatever that may be and for any step downwards the images are downscaled by a factor of 4. (Each side is reduced in half therefore the area is divided by 4. Medium step therefore uses 1/4th of size and low 1/16th.) It is obvious that a higher accuracy setting will lead to the location of more tie points(matches) & better camera alignment, but also, consume more time.
2. *Pair Preselection:* The generic pair preselection is aimed at reducing processing time, since a preselection of pairs with lower accuracy settings is performed, before the actual matching process with the user’s choice of settings. Otherwise, it can be fully disabled or if known/measured camera locations can be input from the reference panel.
3. *Key point limit:* Denotes the upper limit of feature points to be detected (0 = unlimited)
4. *Tie point limit:* Denotes the upper limit of matching points to be detected (0 = unlimited)

**Making use of masking is available at this step.*

Assessment of outcome

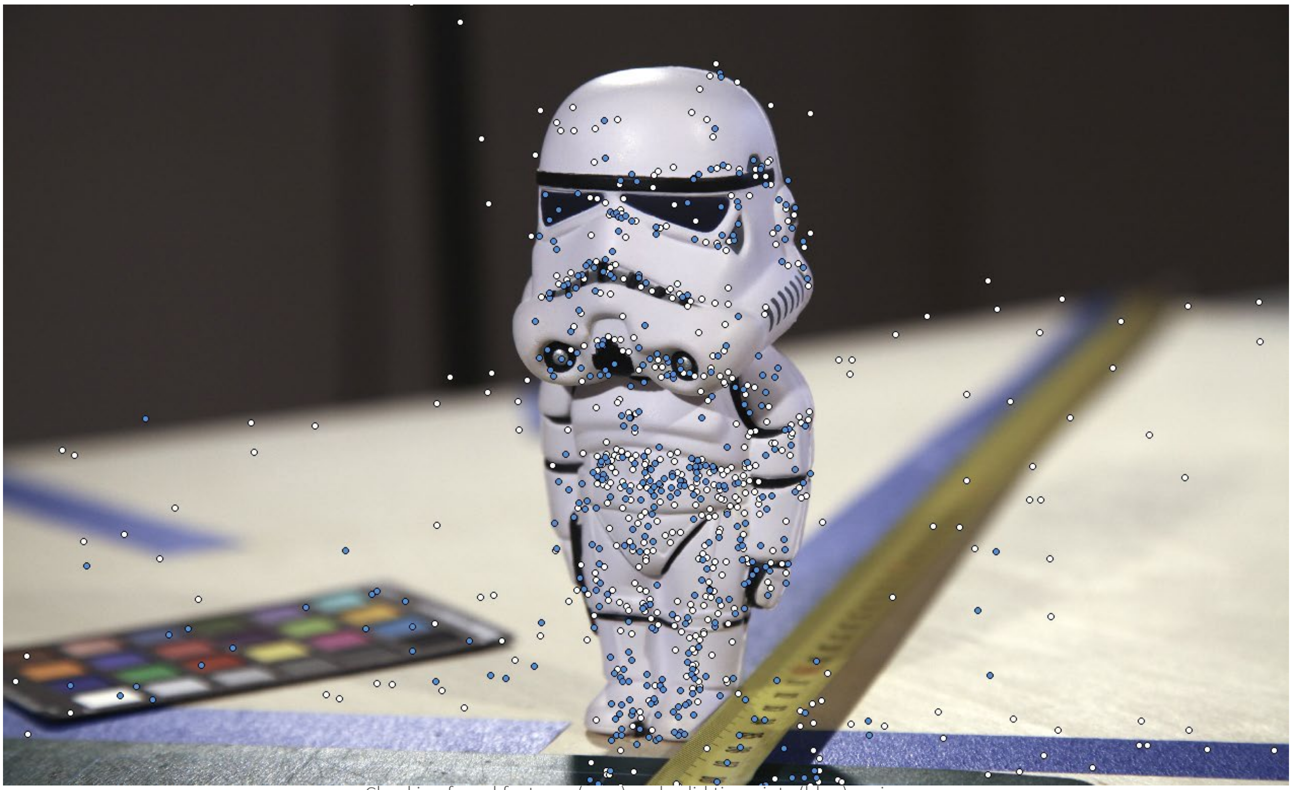
After successful completion of the photo alignment step, one can inspect the outcome. Firstly, one needs to inspect whether all images have been successfully **aligned**. Secondly, one can inspect the found **feature points** and **tie points** on each image as well as the **feature matches** between images to better understand the results of the feature detection and matching process and gain some understanding as to the suitability of the taken photos and their possible improvements.

Aligned Cameras [73/73] & generated Tie point cloud [12.580 points]



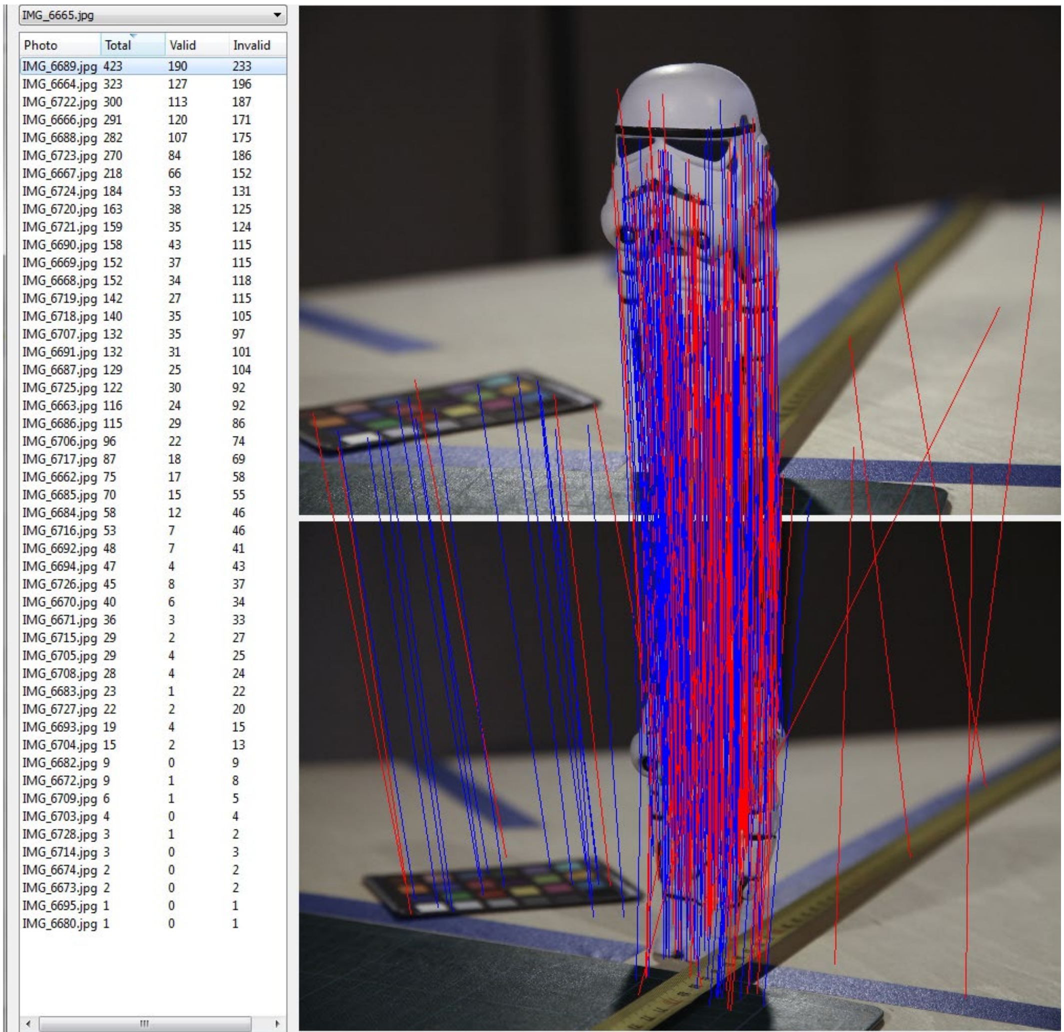
The relative locations of all cameras have been calculated and the target is fully covered

Tie Points on Image



Checking found features (grey) and valid tie points (blue) on image

Feature Matches

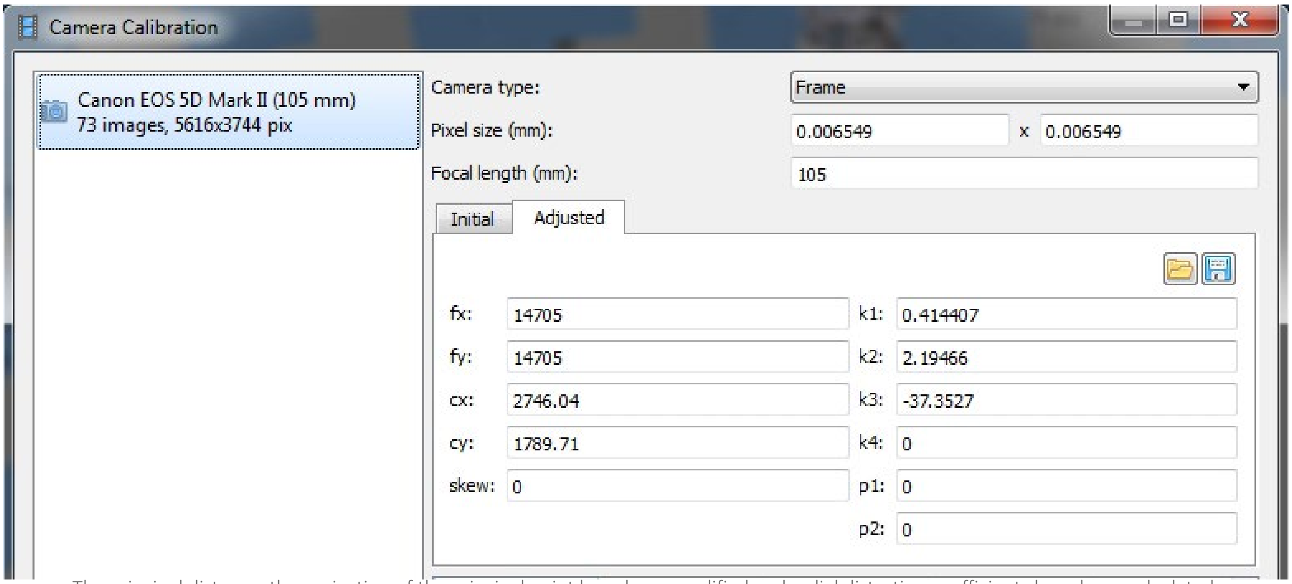


IMG_6665.jpg

Photo	Total	Valid	Invalid
IMG_6689.jpg	423	190	233
IMG_6664.jpg	323	127	196
IMG_6722.jpg	300	113	187
IMG_6666.jpg	291	120	171
IMG_6688.jpg	282	107	175
IMG_6723.jpg	270	84	186
IMG_6667.jpg	218	66	152
IMG_6724.jpg	184	53	131
IMG_6720.jpg	163	38	125
IMG_6721.jpg	159	35	124
IMG_6690.jpg	158	43	115
IMG_6669.jpg	152	37	115
IMG_6668.jpg	152	34	118
IMG_6719.jpg	142	27	115
IMG_6718.jpg	140	35	105
IMG_6707.jpg	132	35	97
IMG_6691.jpg	132	31	101
IMG_6687.jpg	129	25	104
IMG_6725.jpg	122	30	92
IMG_6663.jpg	116	24	92
IMG_6686.jpg	115	29	86
IMG_6706.jpg	96	22	74
IMG_6717.jpg	87	18	69
IMG_6662.jpg	75	17	58
IMG_6685.jpg	70	15	55
IMG_6684.jpg	58	12	46
IMG_6716.jpg	53	7	46
IMG_6692.jpg	48	7	41
IMG_6694.jpg	47	4	43
IMG_6726.jpg	45	8	37
IMG_6670.jpg	40	6	34
IMG_6671.jpg	36	3	33
IMG_6715.jpg	29	2	27
IMG_6705.jpg	29	4	25
IMG_6708.jpg	28	4	24
IMG_6683.jpg	23	1	22
IMG_6727.jpg	22	2	20
IMG_6693.jpg	19	4	15
IMG_6704.jpg	15	2	13
IMG_6682.jpg	9	0	9
IMG_6672.jpg	9	1	8
IMG_6709.jpg	6	1	5
IMG_6703.jpg	4	0	4
IMG_6728.jpg	3	1	2
IMG_6714.jpg	3	0	3
IMG_6674.jpg	2	0	2
IMG_6673.jpg	2	0	2
IMG_6695.jpg	1	0	1
IMG_6680.jpg	1	0	1

Viewing the feature matches between image pairs can help evaluate the photographic input and setup

Adjusted Camera Parameters



The principal distance, the projection of the principal point have been modified and radial distortion coefficients have been calculated.

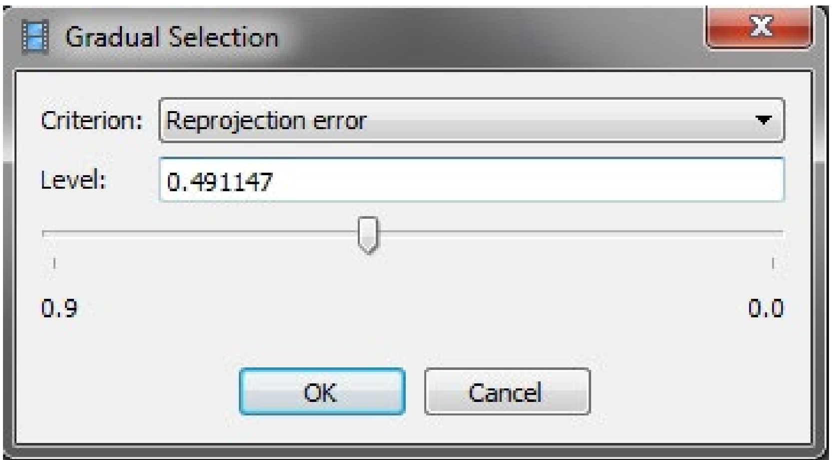
III. Troubleshooting

If not enough coverage of the target is achieved, amendments must be made:

- *Additional photographic capturing session*
- *Disabling/Removing not optimal photographs*
- *Masking the object*
- *Setting Camera Alignment parameters at different values*
- *Input of known camera locations*

IV. Optimization

After the alignment process, a further **optimization of the camera alignment** can take place. The generated tie point cloud can be **filtered** for removal of low accuracy tie points via using the “gradual selection” option with the “reprojection error[26]” filter. Eliminating them can leave a “cleaner” point cloud. On the thinner and more accurate tie point cloud, a second camera calibration and alignment phase can take place which will result in new camera locations and parameters.

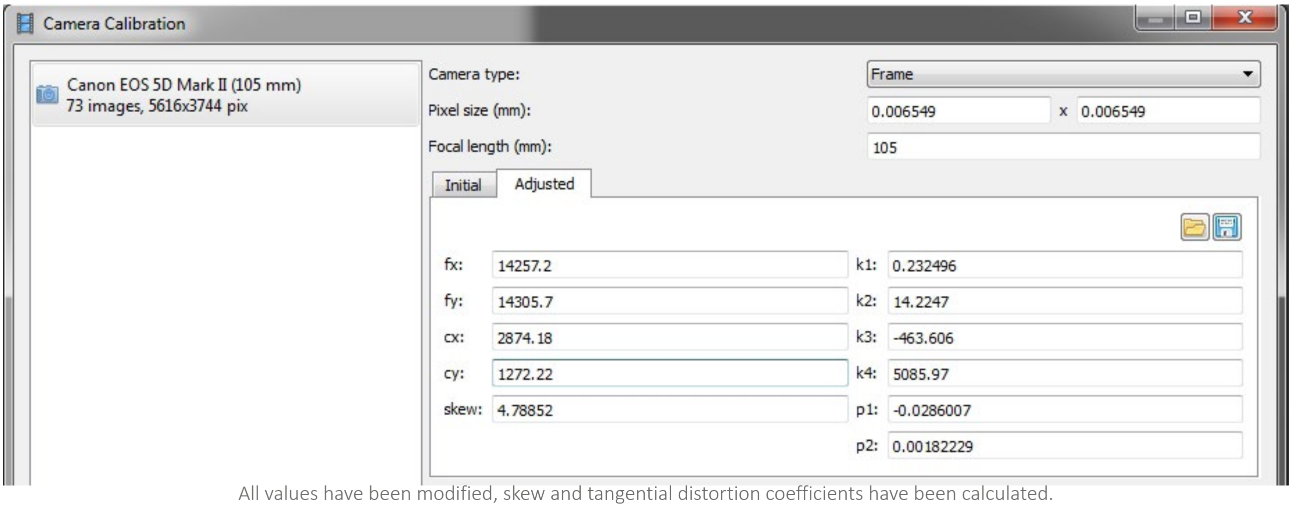


The value of reprojection error for the filtering was set at half of maximum

Filtering removed 1.448 points. Valid Tie points in the background should not be removed, since they will assist the camera optimization process.

26 The reprojection error is a geometric error corresponding to the image distance between a projected point and a measured one. In this case, the measured point refers to the original point coordinates on the image, while the projected point refers to the reprojection of the tie point from its estimated 3d location back on the image plane.

Optimized camera parameters



All values have been modified, skew and tangential distortion coefficients have been calculated.

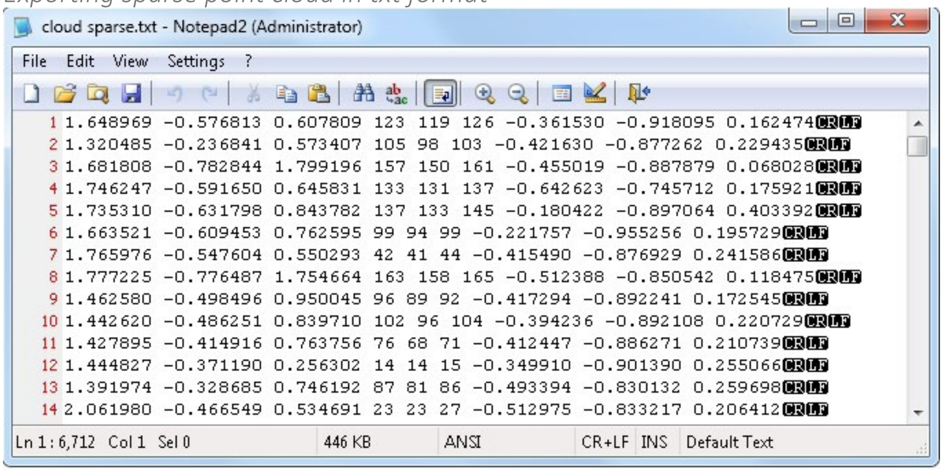
> Exports:

After the conclusion of this step, the following data can be exported.

- camera calibration data
- point matches
- sparse point cloud

** It should be noted that the sparse point cloud will not be used for the dense point cloud generation, which will be calculated anew. Nonetheless, it can be exported and used in external software, if deemed useful. The sparse point cloud can be exported in .obj format.*

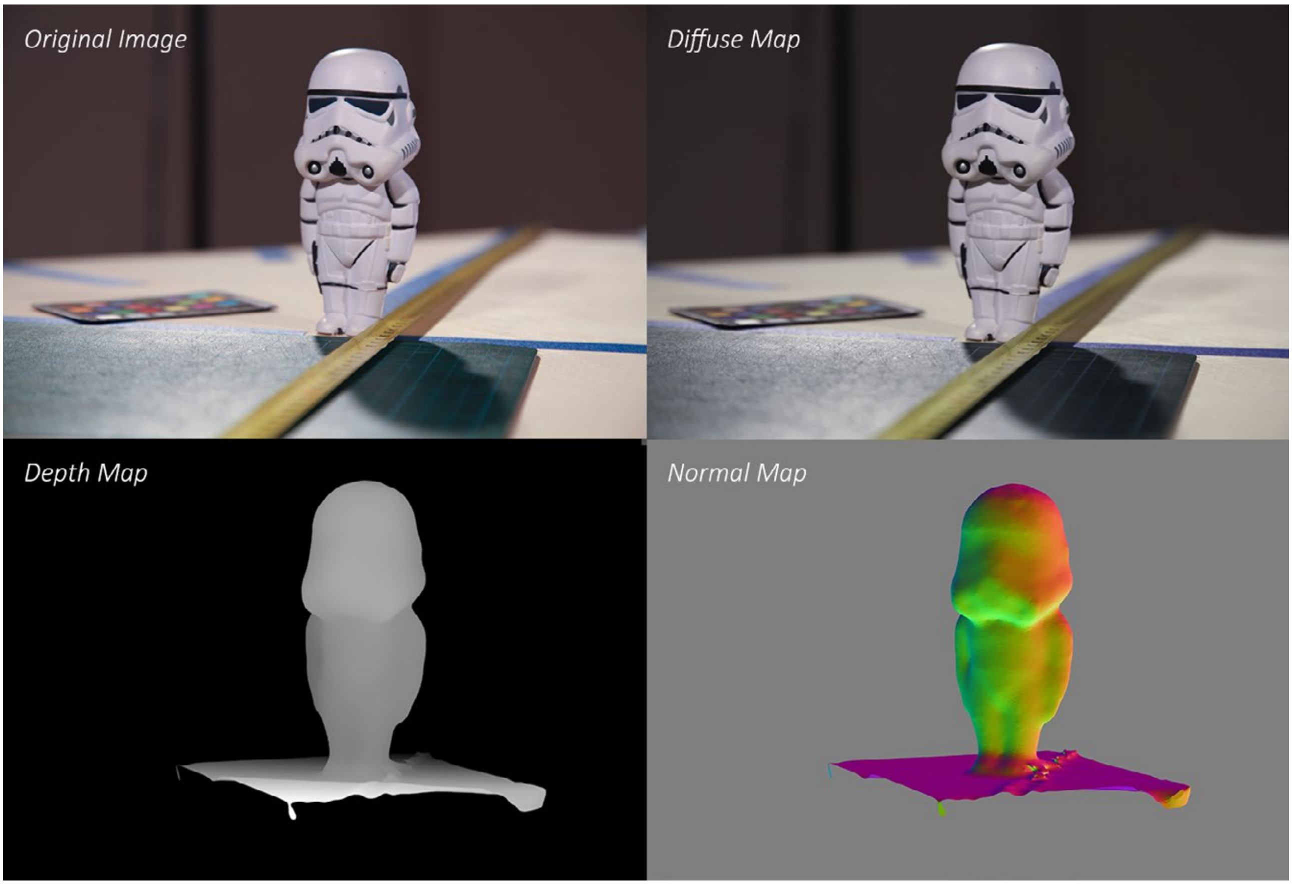
Exporting sparse point cloud in txt format



V. Dense Point Cloud Generation

At this stage, 3d point restitution takes place. For this purpose, **depth, diffuse** and **normal** maps for each (aligned) image are calculated.

Image Maps for the generation of the Point Cloud

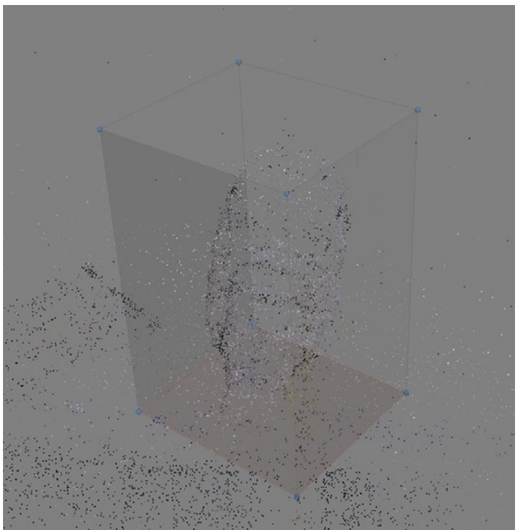


Dense Point Cloud Generation Parameters

1. *Quality:* Quality will determine the size and complexity of the generated point cloud.
2. *Depth Filtering:* Depth filtering helps in the removal of outliers, due to noise, blurriness or poor texturing. It should be set according to level of detail / complexity of object. It is advised to start by using a moderate setting and further adapting, based on the amount of noise of the outcome and the desired level of detail.

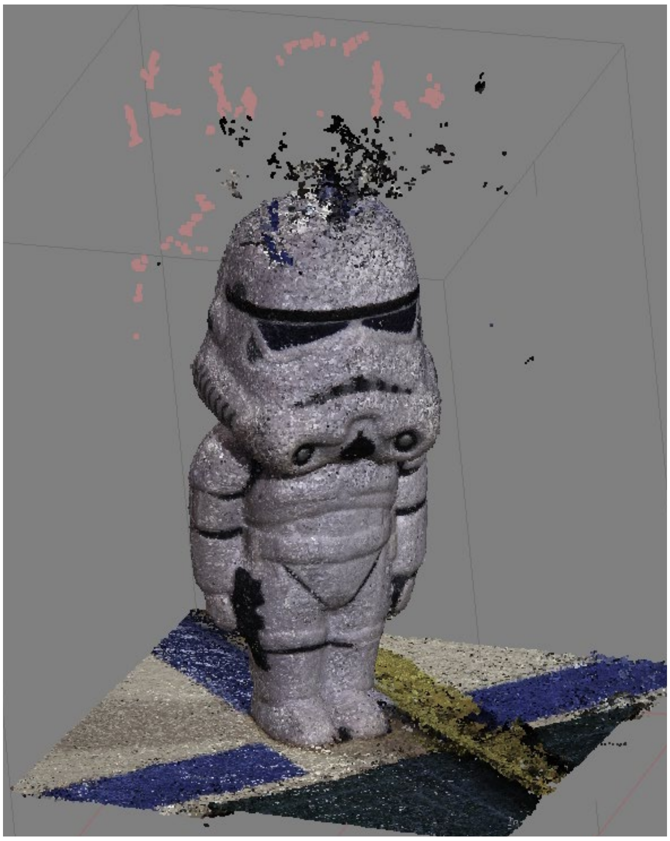
*(*In Medium Quality a dense point cloud of 1453672 was generated.)*

Defining Region for Point Cloud Generation



Region is set only on desired object including the least possible background.

Cleaning Dense Point Cloud & Final Result



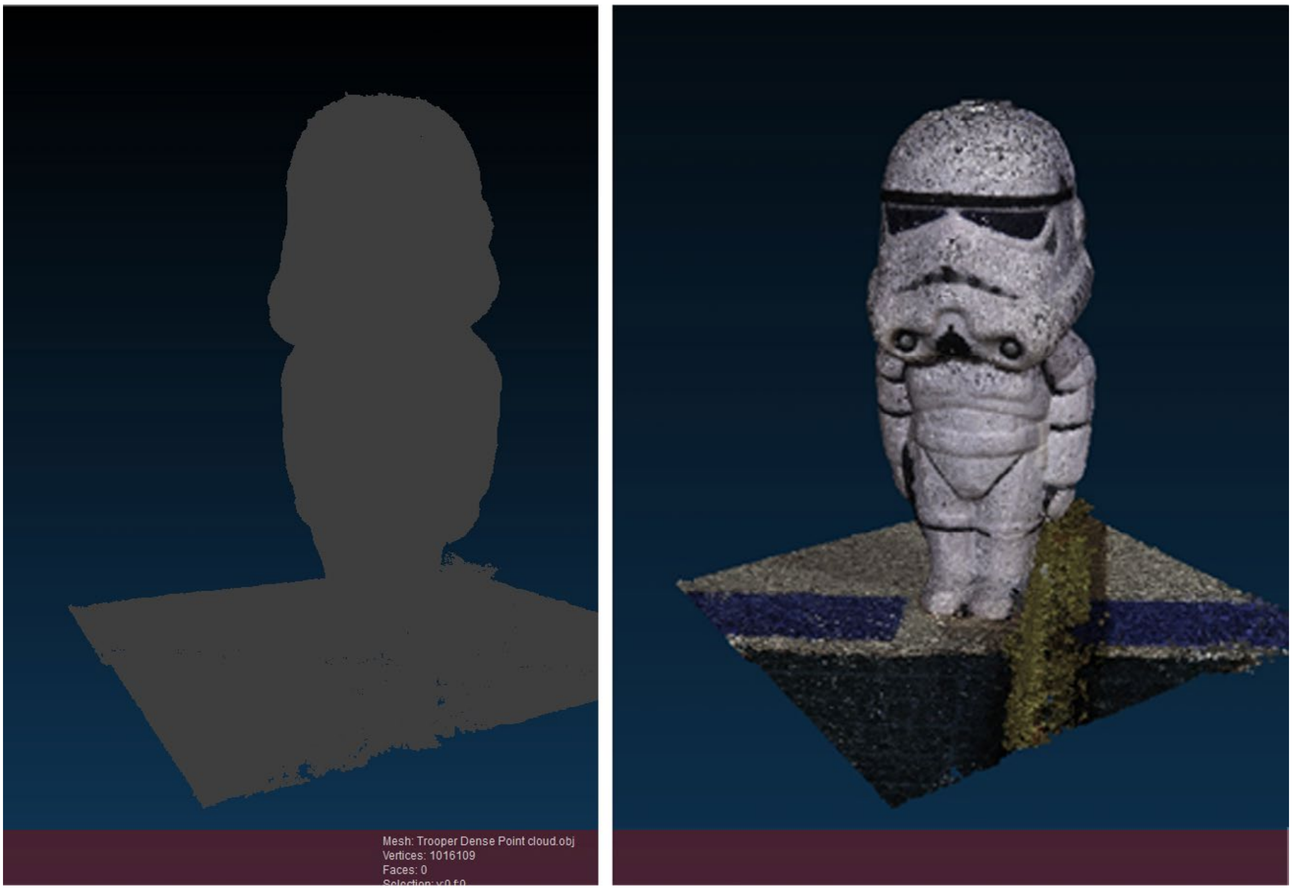
Exporting the Dense Point Cloud for editing in external, dedicated software

A **workflow alternative** is to export the dense point cloud for **editing/filtering** and **mesh generation** in external software:

File Formats

File Format	Extension	Colour Information	Normal Vector
Wavefront	.obj		Y
Stanford	.ply	Y	Y
XYZ Point Cloud	.txt	Y	Y
ASTM E57	.e57	Y	
ASPRS LAS	.las	Y	
Adobe PDF	.pdf		
U3D	.U3D		
Potree	.zip		
Photoscan OC3	.oc3		

Comparison of Point cloud formats



Left: .obj without colour information & Right: .ply with colour information

VI. Polygonal Mesh Generation

Polygonal Mesh Generation Parameters

1. *Surface Type:* Based on the type of object, a suitable setting should be chosen for mesh generation, notably “arbitrary” for solid, 3d objects or “height” for relief/surfaces.
2. *Source data:* In normal cases, the dense point cloud is the most suitable primary input for the generation of the mesh, but the option to use the sparse point cloud, if deemed necessary, is available.
3. *Polygon Count:* The face/polygon count option is normally based on ratio to point cloud, with 1/5, 1/15 and 1/45 ratios respectively. The option to set a custom amount is also available. Keep in mind to strike a balance between too high, which will lead to visualization problems and too low which will lead to undesirably rough meshes.
4. *Interpolation:* The interpolation option refers to the automated hole filling.

> In any case, mesh decimation of various intensity is advised since the polygon count of the generated mesh can deplete processing resources in external 3d handling software.

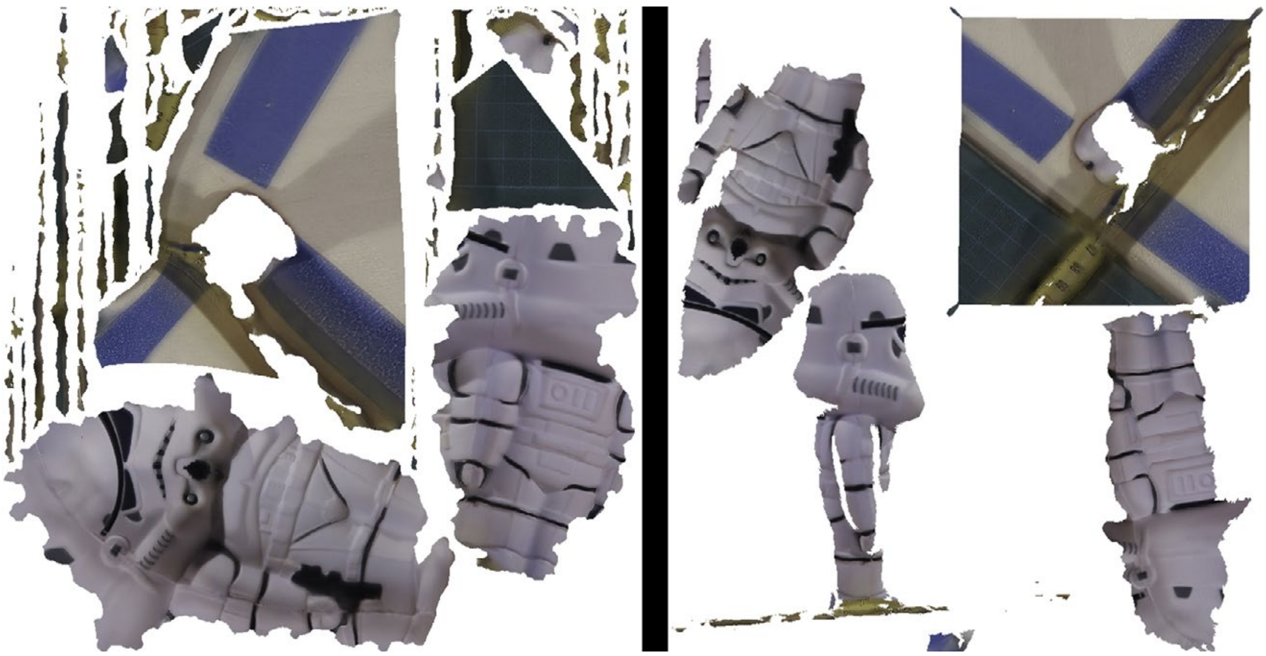
Mesh generation and Mesh edits

VII. Texture Generation

Texture Generation Parameters

1. *Texture mapping mode:* Different mapping modes produce significantly different results in terms of uv mapping and texture generation. Generic mode is the norm, while adaptive orthophoto mode will divide regions in horizontal and vertical areas and use suitable projections to create the atlas. The choice should be based depending on object type and project needs.
2. *Blending mode:* Blending mode defines the method with which the colour information from the original images is combined to determine the pixel colour information of the texture. Mosaic mode will determine the most “appropriate” photo and use the given pixel value. Average will combine the values from all images and calculate an average. Maximum and minimum intensity will correspondingly choose a single colour value for each pixel from the available images.
3. *Texture size count:* Determines the size in pixels of the texture atlas and the number of files that the texture is exported to. Exporting in multiple files can help to achieve maximum texture resolution in cases of limited RAM.

Comparison of different Texture mapping modes

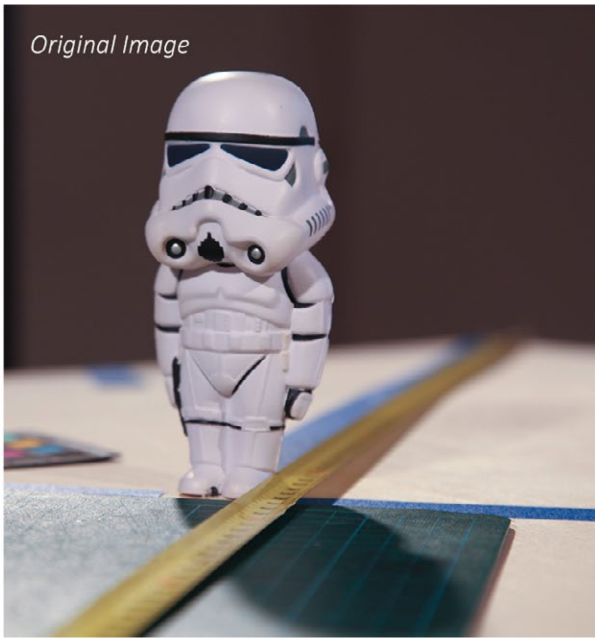


Left: Generic Mode & Right: Adaptive Orthophoto mode

Final Result

Detail

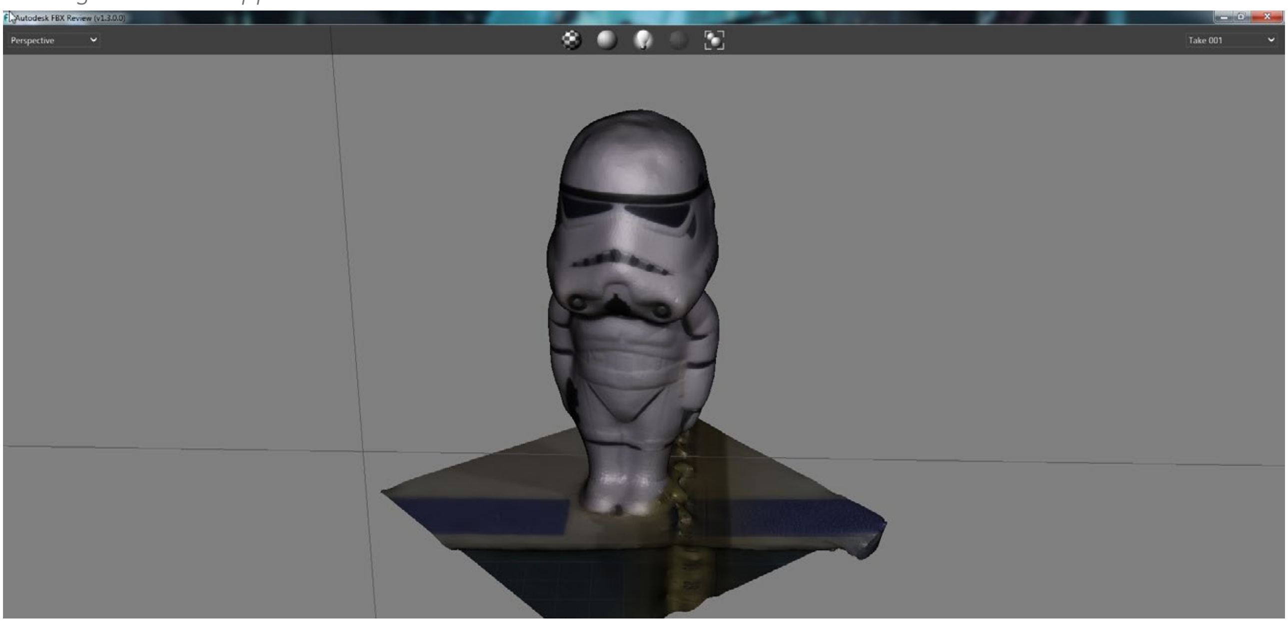
Using the "Look-through" viewing option to compare results



Exporting the textured mesh in File Formats for further edits in external software:

File Format	Extention	Separate texture file
Wavefront	.obj	Y
3DS file format	.3ds	Y
VRML		Y
COLLADA	.	Y
Stanford PLY	.ply	Y
Autodesk FBX	.fbx	Y
Autodesk DXF	.dxf	
Google Earth	.kmz	
U3D		
Adobe PDF		

Viewing in external application: Autodesk FBX



VIII.Georeferencing the model

The model that has been created is **scaleless** and in a **random coordinate system**. The last photogrammetric task is to place it in a **desired coordinate system** in its **real dimensions**. After the correct scaling of the model, measurements can be made and automated calculation of its area and surface is provided. A coordinate system can be defined either by input of **camera locations** or by placing and referencing **markers**. Setting a coordinate system based on camera locations is a faster process, but accurate information of camera positions might not be easy to attain. For this reason the marker approach was preferred.

Placing markers

Markers have various purposes: **setting coordinate system** and thus **scaling the model**, **photo alignment optimization**, **defining lengths** for measurements and finally, **marker based chunk alignment**, intended for large/heavy projects that need to be broken into multiple chunks(parts). Markers are manually placed on the images and each marker is advised to appear in as many images as possible for higher accuracy (at least 2 photos are needed).

- Manual marker placement can take place before camera alignment and each marker needs to be manually identified in all images where it appears.
- If camera alignment has already been performed, guided marker placement is available, which leads to the automated location estimation of the marker in all other images. The automated locations can be manually refined.

After camera alignment, markers can also be placed directly on the 3d model, but this method can lead to lower accuracy.

Assigning coordinates to markers

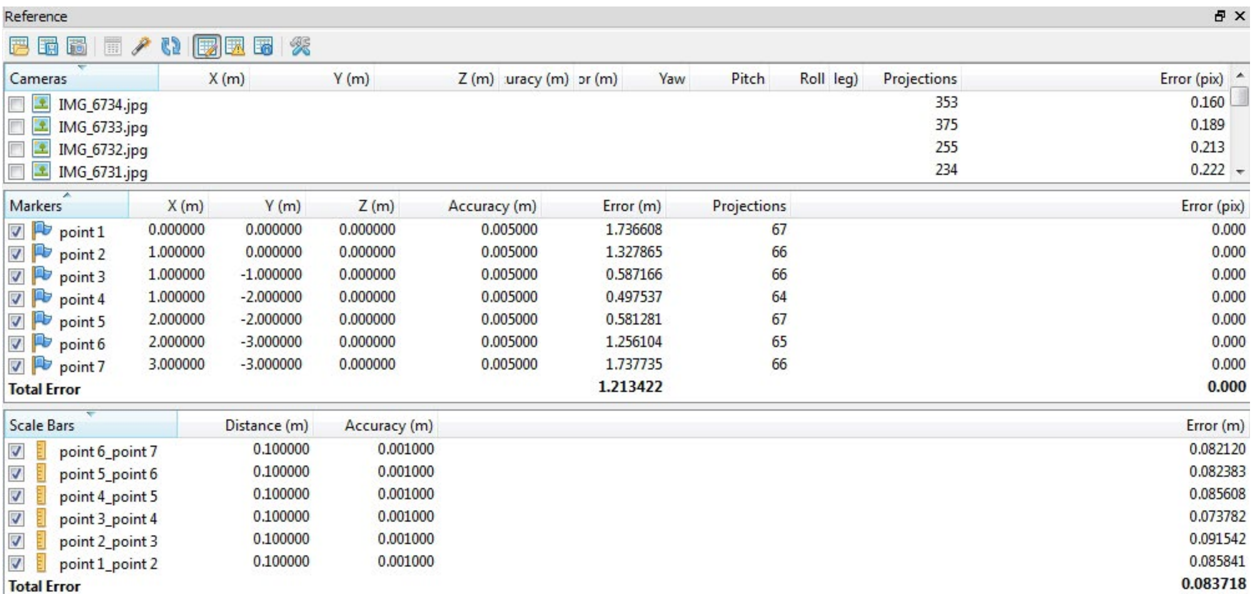
In case that a geographic coordinate system is not required, an arbitrary coordinate system is used, based on project needs. The markers exact coordinates in the chosen system need to be manually input on the reference panel. In the application example, a grid was incorporated in the photo-shooting and kept in the final model to facilitate this process. An arbitrary point of the grid is selected as the origin of the 3-axis system and other points of the grid are chosen as markers, which have easily defined coordinates.

> Thus, the model is reoriented and scaled.

Creating scale bars

Creating **scale bars** are another option for **scaling the model**, in case that setting a new coordinate system is not needed. Scale bars are defined between existing markers and their length measurement can be manually input in the reference panel.

Reference Panel Overview


Reference

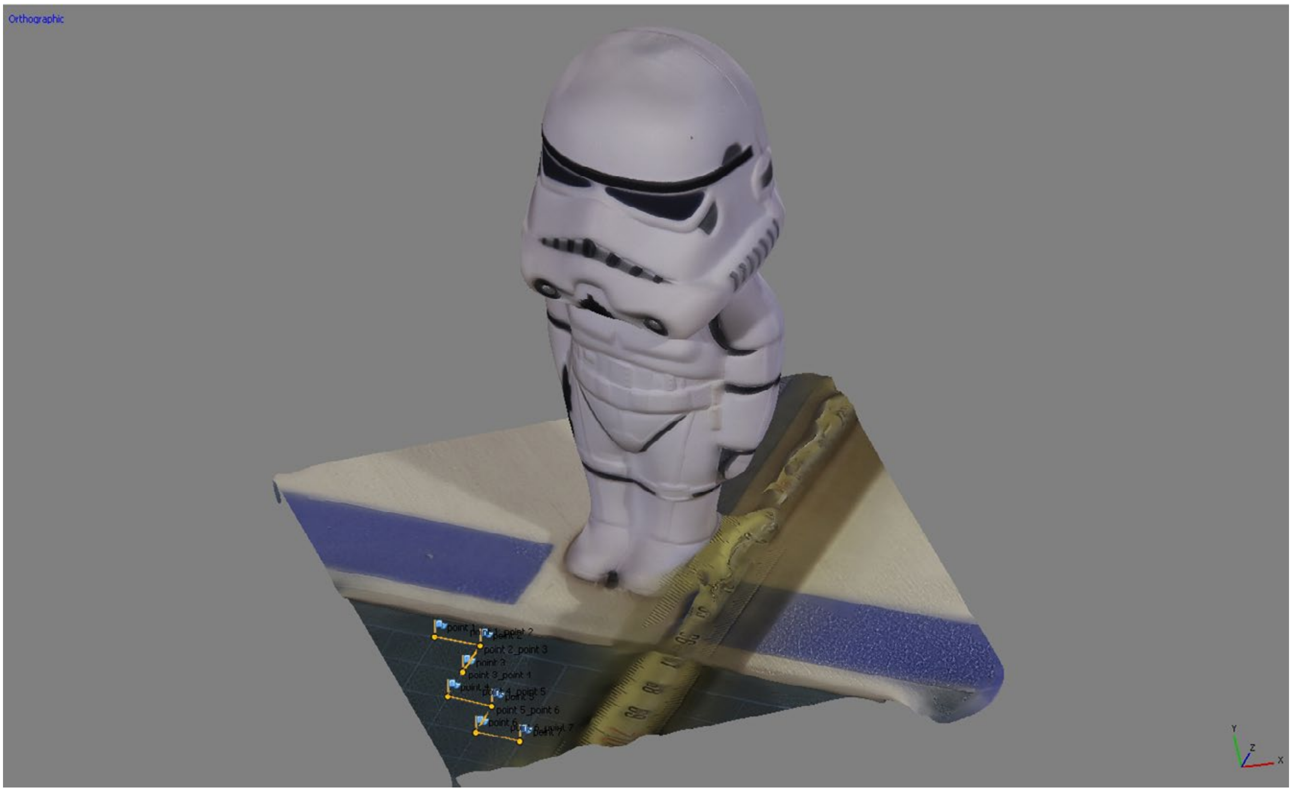
Cameras	X (m)	Y (m)	Z (m)	uracy (m)	ɔr (m)	Yaw	Pitch	Roll	leg)	Projections	Error (pix)
IMG_6734.jpg										353	0.160
IMG_6733.jpg										375	0.189
IMG_6732.jpg										255	0.213
IMG_6731.jpg										234	0.222

Markers	X (m)	Y (m)	Z (m)	Accuracy (m)	Error (m)	Projections	Error (pix)
point 1	0.000000	0.000000	0.000000	0.005000	1.736608	67	0.000
point 2	1.000000	0.000000	0.000000	0.005000	1.327865	66	0.000
point 3	1.000000	-1.000000	0.000000	0.005000	0.587166	66	0.000
point 4	1.000000	-2.000000	0.000000	0.005000	0.497537	64	0.000
point 5	2.000000	-2.000000	0.000000	0.005000	0.581281	67	0.000
point 6	2.000000	-3.000000	0.000000	0.005000	1.256104	65	0.000
point 7	3.000000	-3.000000	0.000000	0.005000	1.737735	66	0.000
Total Error					**1.213422**		**0.000**

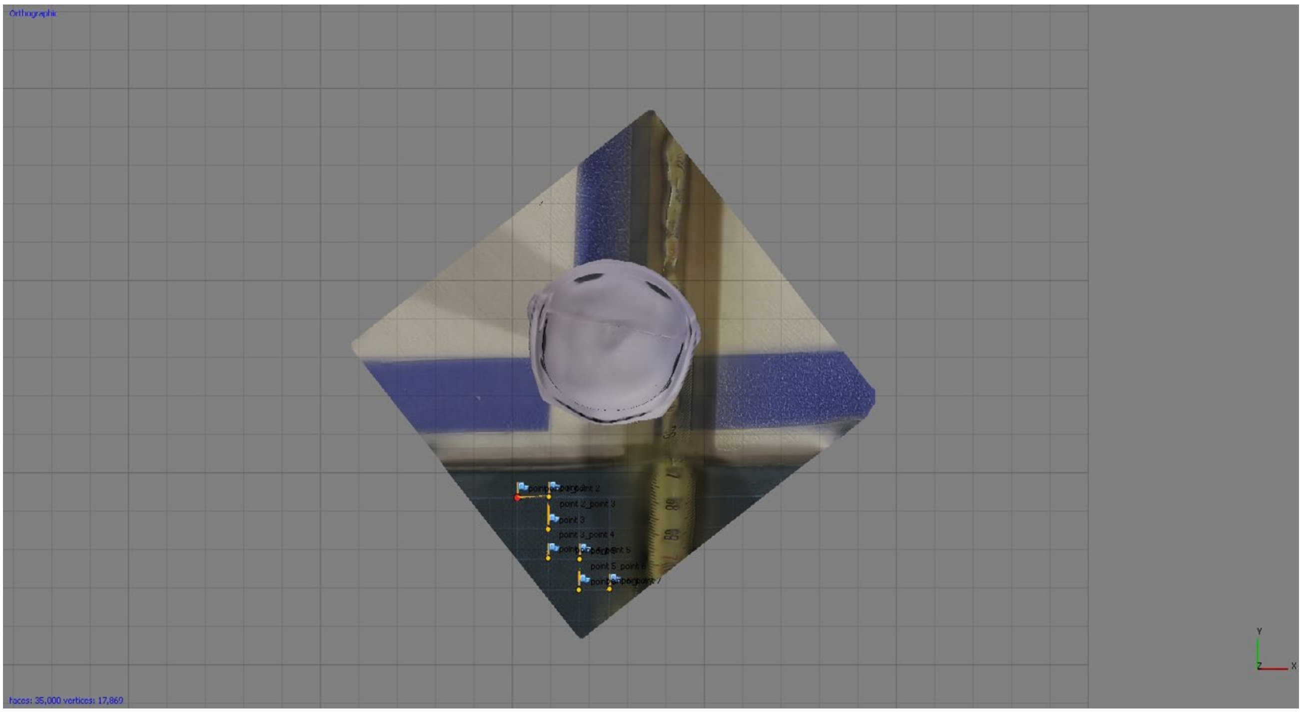
Scale Bars	Distance (m)	Accuracy (m)	Error (m)
point 6_point 7	0.100000	0.001000	0.082120
point 5_point 6	0.100000	0.001000	0.082383
point 4_point 5	0.100000	0.001000	0.085608
point 3_point 4	0.100000	0.001000	0.073782
point 2_point 3	0.100000	0.001000	0.091542
point 1_point 2	0.100000	0.001000	0.085841
Total Error			**0.083718**

The cameras have not been georeferenced. The placed markers and their coordinates are visible, as well as the created scale bars and their lengths.

Placing Markers



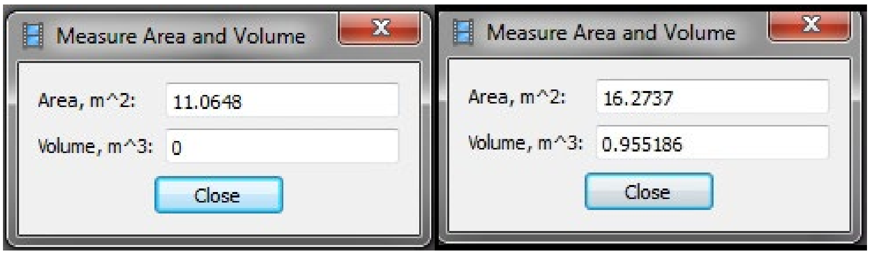
Final Result



The model is viewed top down in the new coordinate system, as displayed by the XYZ-axis symbol on the lower right corner. For better viewing it is set in orthographic projection with visual help of a grid.

Calculating Area and Volume

After setting the coordinate system, **length measurements** can be performed and **automated calculation of the area and volume** of the model is supported.

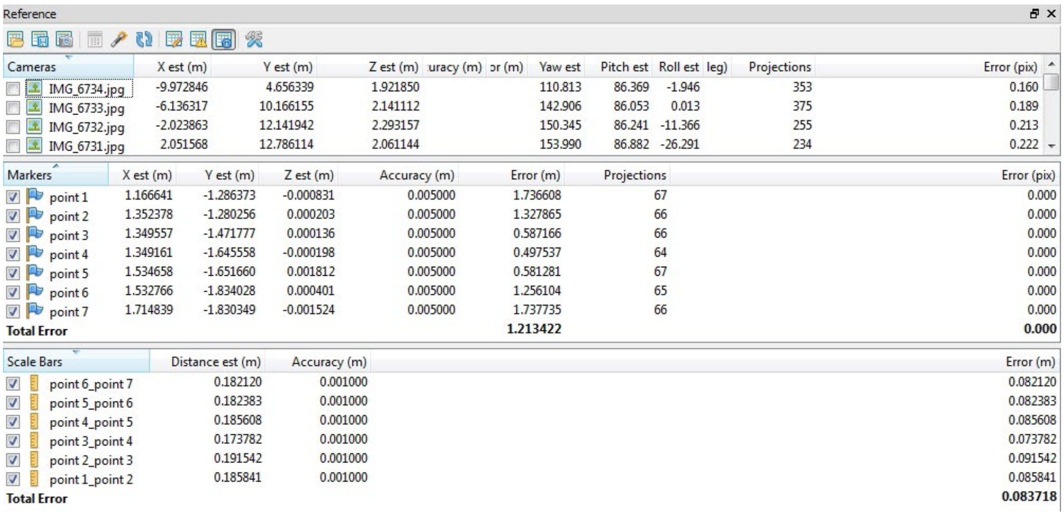


Volume calculation is possible only after closing the holes of the model.

Reference Panel Error & Project Report

After georeferencing the model, an **error report** is available between the input and estimation data, namely between the input and the estimated locations for the cameras, the markers, and between input and estimated length for the scale bars.

Error Report



Reference

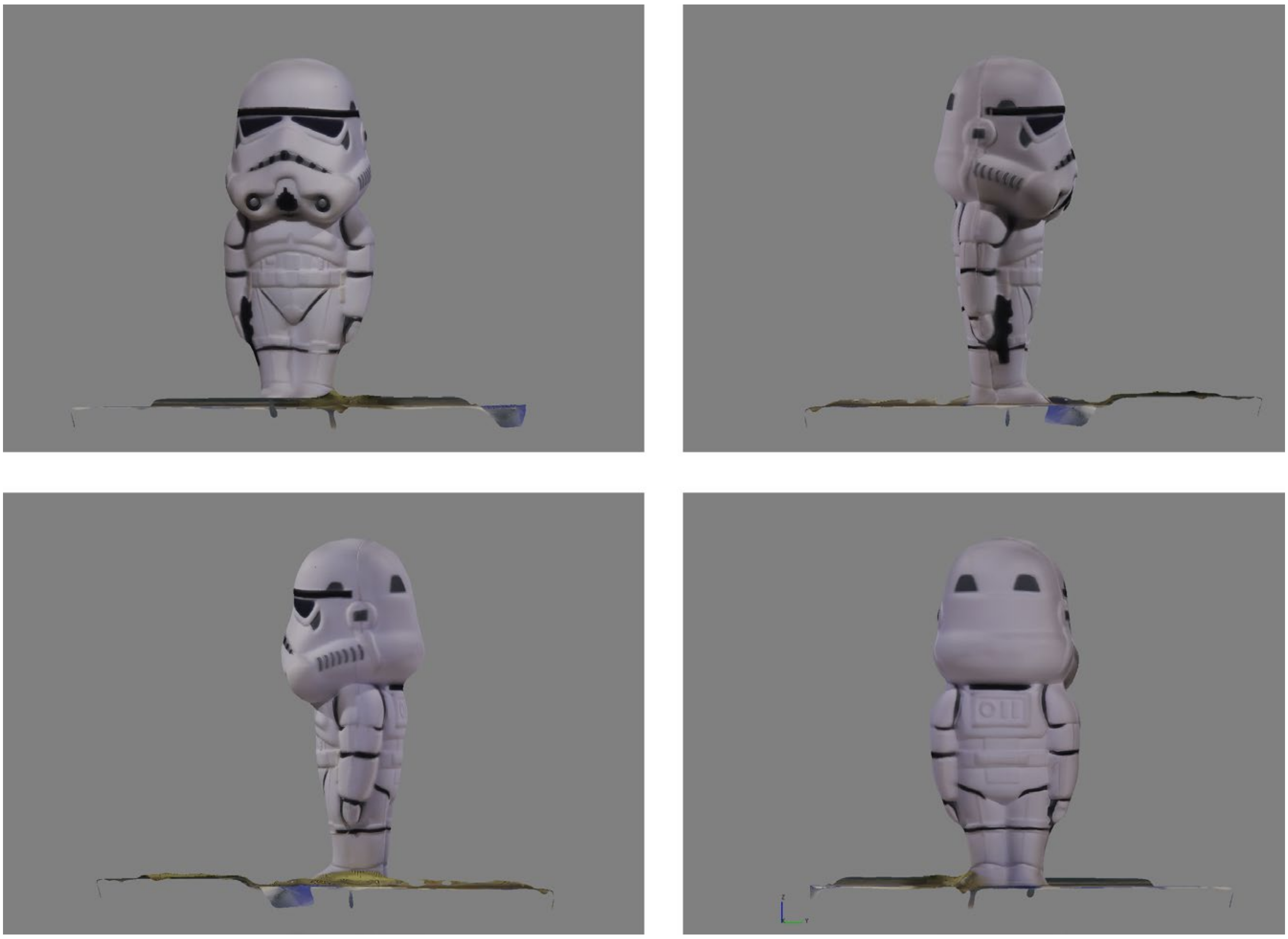
Cameras	X est (m)	Y est (m)	Z est (m)	uracy (m)	or (m)	Yaw est	Pitch est	Roll est	leg)	Projections	Error (pix)
IMG_6734.jpg	-9.972846	4.656339	1.921850			110.813	86.369	-1.946		353	0.160
IMG_6733.jpg	-6.136317	10.166155	2.141112			142.906	86.053	0.013		375	0.189
IMG_6732.jpg	-2.023863	12.141942	2.293157			150.345	86.241	-11.366		255	0.213
IMG_6731.jpg	2.051568	12.786114	2.061144			153.990	86.882	-26.291		234	0.222

Markers	X est (m)	Y est (m)	Z est (m)	Accuracy (m)	Error (m)	Projections	Error (pix)
point 1	1.166641	-1.286373	-0.000831	0.005000	1.736608	67	0.000
point 2	1.352378	-1.280256	0.000203	0.005000	1.327865	66	0.000
point 3	1.349557	-1.471777	0.000136	0.005000	0.587166	66	0.000
point 4	1.349161	-1.645558	-0.000198	0.005000	0.497537	64	0.000
point 5	1.534658	-1.651660	0.001812	0.005000	0.581281	67	0.000
point 6	1.532766	-1.834028	0.000401	0.005000	1.256104	65	0.000
point 7	1.714839	-1.830349	-0.001524	0.005000	1.737735	66	0.000
Total Error					**1.213422**		**0.000**

Scale Bars	Distance est (m)	Accuracy (m)	Error (m)
point 6_point 7	0.182120	0.001000	0.082120
point 5_point 6	0.182383	0.001000	0.082383
point 4_point 5	0.185608	0.001000	0.085608
point 3_point 4	0.173782	0.001000	0.073782
point 2_point 3	0.191542	0.001000	0.091542
point 1_point 2	0.185841	0.001000	0.085841
Total Error			**0.083718**

IX. Final Result

The 4 orthographic views of the final model



X. General Project Management

Keeping track

- Using the console view provides important information about the algorithm processes
- Saving a log of the console view can help analyse performance with scrutiny for project optimization

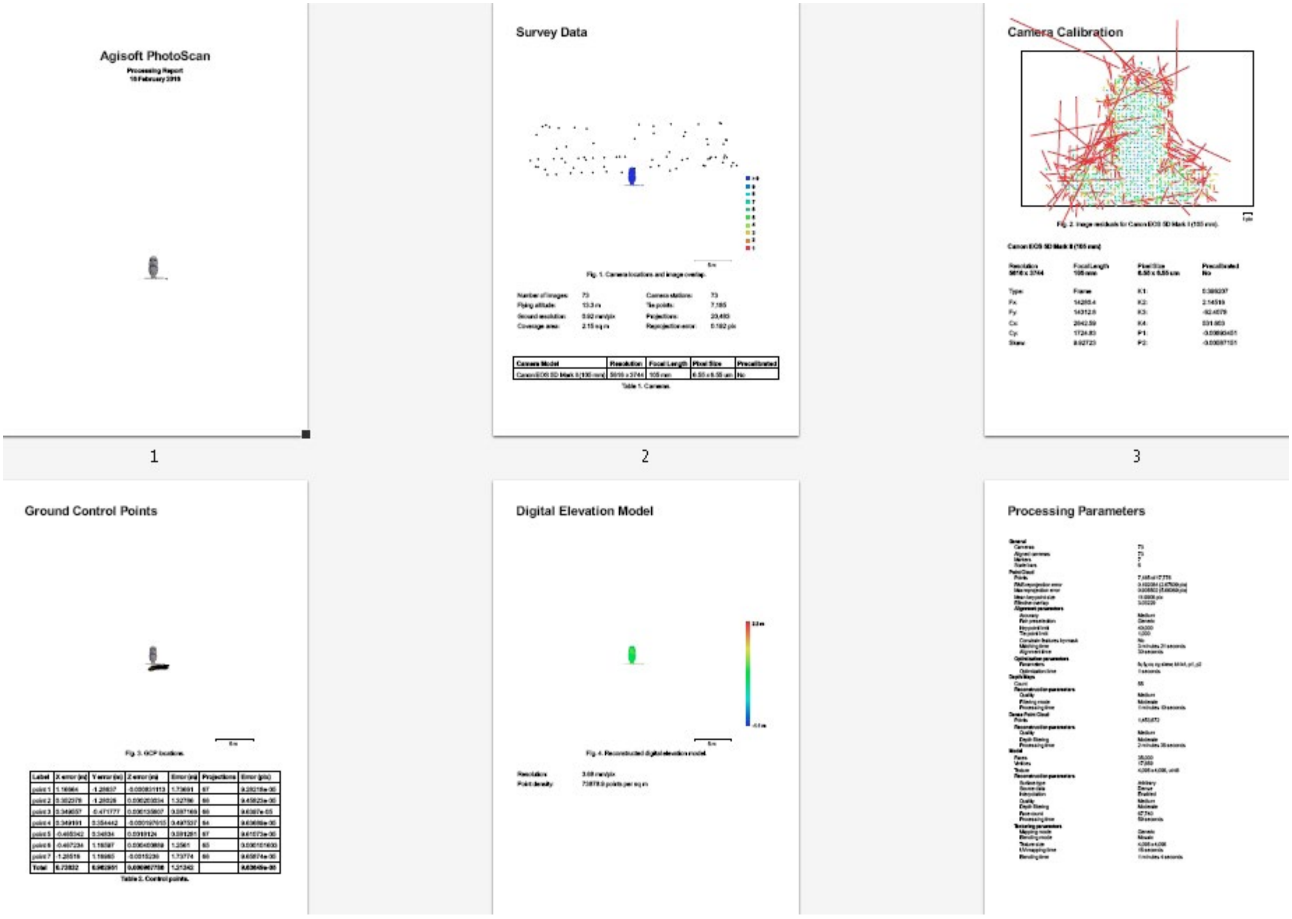
Saving a project

The following elements are stored when saving the photogrammetric project:

- List of loaded photographs with reference paths to the image files.
- Photo alignment data such as information on camera positions, sparse point cloud model and set of refined camera calibration parameters for each calibration group.
- Masks applied to the photos.
- Dense point cloud model with information on points classification.
- Reconstructed 3D polygonal model with any changes made by user. This includes mesh and texture if it was built.
- Depth maps for cameras.
- List of added markers and information on their positions.
- Structure of the project, i.e. number of chunks in the project and their content.

Project Report

Apart from that, report generation for every of the 6 planes is available after project completion that records all of the project parameters as well as detailed data for the reconstruction accuracy of each plane.

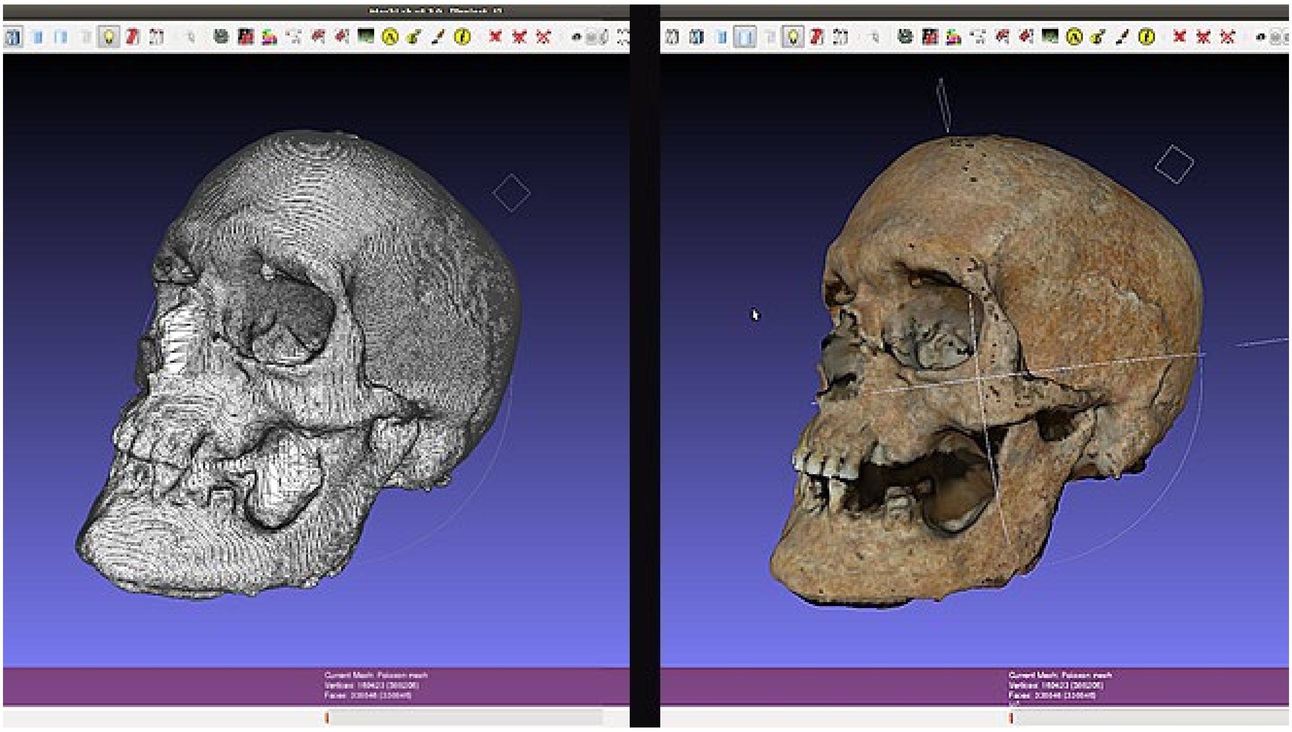


POST-PROCESSING

Geometric Edits

Another workflow option is to export the dense point cloud from the photogrammetric software and continue further work on external software. This is especially the case when using open source photogrammetric software or toolboxes for bundle adjustment and 3d point restitution, such as VisualSfm. A common choice for open-source[27] software for processing of point clouds is **MeshLab[28]**, which was originally created for the post-processing of the point clouds generated by laser scanners. It is ideal also for editing point clouds generated by photogrammetric software, as well as triangular meshes. Edits can be manual or automated, for tasks such as:

- Editing and filtering of **point clouds**
    - noise reduction
    - hole filling
- **Generation** of **meshes**
- **Editing** of **meshes**
    - mesh smoothing
    - mesh decimation
    - hole filling



Reconstruction of triangular mesh from point cloud with Poisson Algorithm and texturing of mesh with Vertex Attribute Transfer in MeshLab[29]

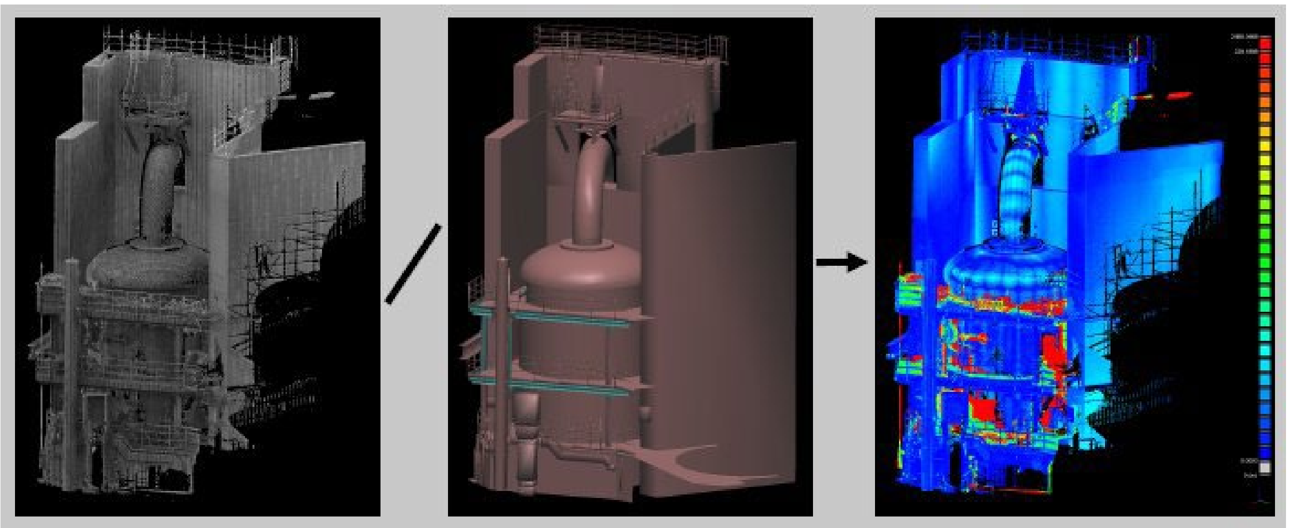
27 Object to GNU General Public License (GPL), version 2 or later

28 Created at 2005 by the University of Pisa, Italy and developed by the ISTI - CNR (Institution of Information Science & Technology - National Research Council, Italy) research centre || http://meshlab.sourceforge.net/

29 Source Images from : http://arc-team-open-research.blogspot.gr/2012/05/forensic-facial-reconstruction-with.html

Evaluation with reference

In certain occasions, there is a need for accuracy estimation of the output based on a certified reference file or more often, comparison and evaluation between alternative outputs from the same or other documentation methods (such as laser scanning). For this purpose, specific software can be used, which can perform **comparison between point clouds** or between **point cloud & triangular mesh**. An open source alternative to this is “Cloud Compare[30]” by Daniel Girardeau-Montaut (2006).



Comparison between point cloud, triangular mesh and distance calculations result[31]

30 http://www.danielgm.net/cc/
31 http://www.danielgm.net/cc/

VII. AFTER MODEL ACQUISITION

If Close-Range Photogrammetry can be summed up as a method for the "Documentation of Objects & their Arrangement in Space", 3 broad action-plans can be presented on how to proceed with the resulting outcome:

> Viewing :

Study > Show & Distribute for educational and informational purposes

> Modifying/Using :

Modify/use the output model for further analysis or implementation in applications

>Recreating:

Reproduce/recreate a physical objects or model supplements according to the digital mould

Based on this threefold division, a presentation will follow about some possibilities on viewing\distributing the models, further modifying them for an end purpose and finally creating physical copies of the models.

3d Model of artifact from the National Constitution Center in Independence National Historical Park (INHP), Philadelphia. Model and Texture by photogrammetric means, Digital assets uploaded to web-service and used for public media announcements[32]

32 http://www.dayofarchaeology.com/tag/photogrammetry/

VIEWING

Along with the proliferation of 3d content arises the need for easy and stable sharing of information. For the dissemination of 3d content, the following 3 options are commonly available:

- hosting in servers and viewing with web-browsers with or without various plug-ins
- installing stand alone free to use/open source viewers
- embedding in pdf format

I. Web-Hosting Services for 3d models

- X3dom.org
- Verold.com
- GrabCad
- 3dVia
- p3D
- Unity 3d

Model Libraries, hosted by software or hardware companies, with additional services

Most companies offering photogrammetric web-services also offer web hosting services for the 3d models, together with a community hub/forum. In the same spirit, companies offering 3d printers or printing services likewise offering hosting services. Examples are:

- 123D Gallery
- Sketchfab
- Shapeways
- Thingiverse
- Makerbot Digital Store
- the Trimble 3D Warehouse

Model Libraries with free to use models

Given the extent of the CGI and 3d modelling industry, the sites offering models and space for storing them are numerous. When the content is not for sale, they operate mostly on embedded advertisements.

- Archive3D.net
- Google 3d Warehouse
- 3DModelFree

Model Marketplaces for professionals

Given the increased interest in 3d models, specific "marketplace" sites have long been created which extend the hosting and viewing services to sale support. Examples are:

- Turbosquid
- Formfonts
- 3D Total

II. Stand alone 3d Model Viewers

Nowadays, various lightweight viewers are available either as open source, developed by communities and individuals, or distributed as free to use from the companies offering the mainly used software packages.

Depending on the desired file format, the user may find alternatives, a sort exemplary list follows:

- AssimpView
- GLC-Player
- Open 3D Model Viewer
- Meshlab
- FBX® Review (free to use, by Autodesk)

III. Embedding 3d Models in Pdf File Format

One of the (relatively) upcoming and important methods for the dissemination of 3d content is the integration in the ubiquitous pdf format for two important reasons: it disengages from the need of internet access and the terms under which the remote file hosting is supplied and also it doesn’t require any special software installation on the receiving end, which might further complicate or delay the information exchange. For this purpose 2 formats have been standardized: the PRC[33] and U3D.

About Universal 3D format [U3D]

Described as «an extensible format for downstream 3D CAD repurposing and visualization», the U3D was defined by a special consortium called 3D Industry Forum[34] and later standardized by Ecma International in 2007(4rth edition)[35]. The purpose was to create a universal standard for three-dimensional data of all kinds, to facilitate data exchange. In practice, the format is primarily used for 3D PDF internal encoding, rather than as an interchange format. The file format finds extensive use in many business applications (specifically industrial manufacturing, as well as construction and plant design) and research fields (biomedical, chemistry, astronomy). Other applications include the completion of technical reports used in engineering, manufacturing, medical, aerospace, geology, geophysics, civil engineering, environmental surveys, and as an interoperable file format for Computer-Aided Manufacturing (CAM), Product Life-Cycle Management (PLM) for supply-chain, training, marketing, archiving and engineering reports.

Definition

U3D is a general 3D graphics format, primarily best suited to triangle meshes, lines and points with hierarchical structure, colour and texture. Attributes can be attached to 3D objects, as embedded metadata. It allows for geometric surface visual representations, composed of tessellated (triangulated) surface geometry meshes. Features of the format include CLOD Representations (variable resolutions using «Continuous Level of Detail», aka CLOD method, providing lower polygon count versions of the original high resolution model) and Animation Displacement Channels (Mesh node displacement channels, allowing for movement of parts over time).

Applications that can embed and render U3D

The U3D format is natively supported by the PDF format[36] but the U3D file format specification does not address issues regarding rendering of 3D content - that is handled by the PDF rendering software.

Adobe Reader supports rendering U3D since version 7[37]. Adobe Acrobat supports exporting to standalone U3D files, creating pdf files containing U3D, as well as inserting externally created U3D into existing pdfs. Open source solutions for embedding U3D in pdfs this include Itext and Latex (with Miktext package)[38].

Applications that generate U3D files

There is a certain number of 3d geometry applications that

1. can natively generate 3d content in U3D format
2. export directly to pdf containing the model in U3D.
3. function as standalone/external translators of 3d models to U3D[39].

Of the various 3d modelling programs that can export textured 3d geometry to U3D, the most common

33 The PRC (Product Representation Compact) is a file format which stores geometry as polygons and offers various levels of compression. It is mostly used in industry workflows.

34 Founded by a diverse group of companies and disbanded, replaced by 3D PDF Consortium.

35 Format Specification found here: > http://www.ecma-international.org/publications/standards/Ecma-363.htm

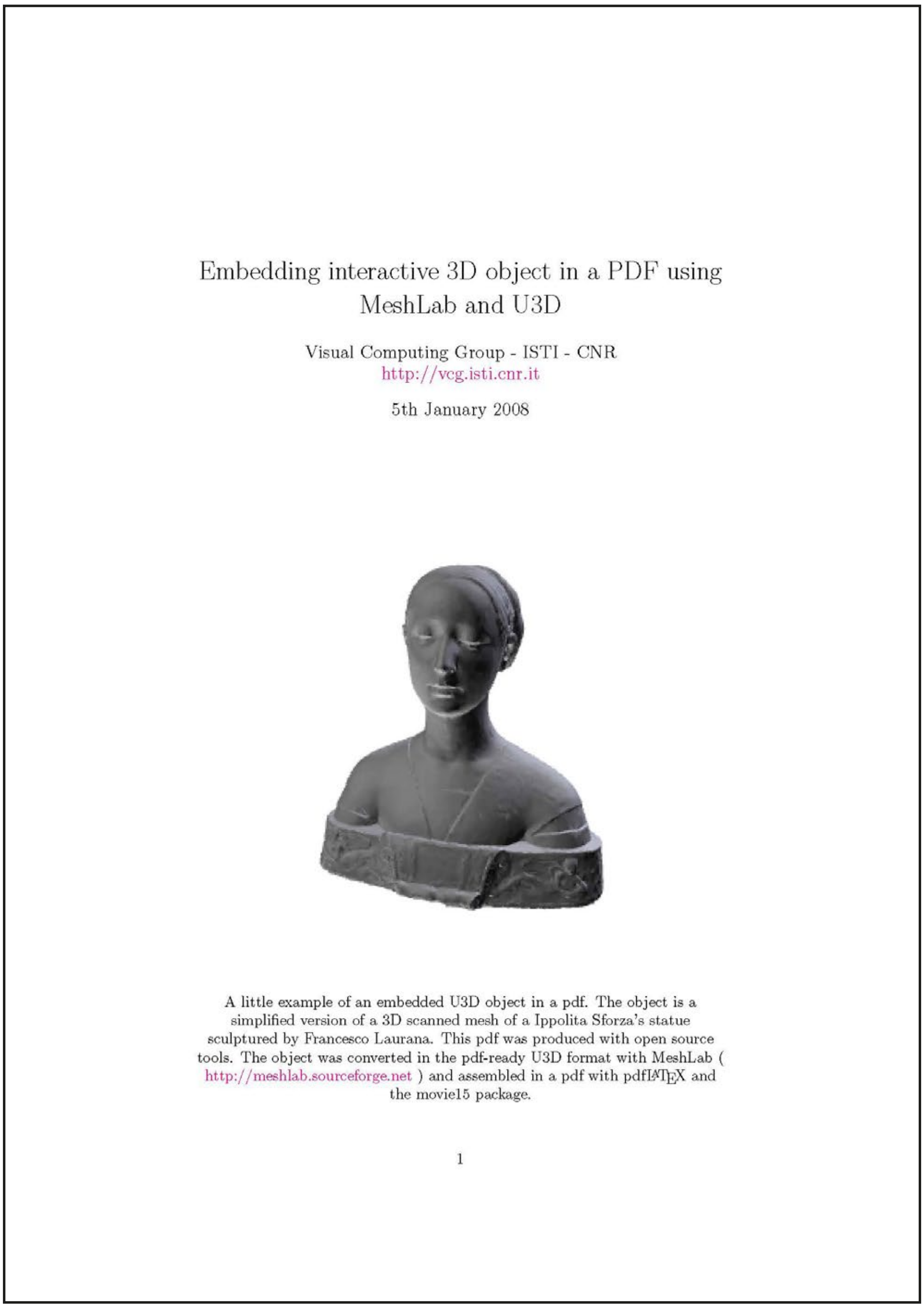
36 PDF was developed by Adobe. Portable Document Format. It is a document description language, used to define electronic documents independently of its creating, displaying and printing
software, hardware and operating system
A PDF file encapsulates all resources to completely describe the content and layout of an electronic document, including texts, fonts, images and ultimedia elements without the need of external resources.

37 Since Adobe was one of the companies in the forum.

38 Movie15 latex package

39 http://www.pdf3d.com/U3D.php
http://www.okino.com/conv/exp_U3D.htm

architectural suite would be ArchiCAD[40], while the most popular open source alternative is Meshlab. Furthermore, MatLab libraries have been developed for the same purpose.[41] There are also open source Java libraries[42], accessible for familiarized users to implement in their own workflow or for the development of related applications. Exporting directly to pdf files containing embedded U3D can be through software such as Solidworks (CAD / CAE software), Microstation by Bentley System and ArtiosCAD (folded packaging, corrugated boxes and folding carton, by packaging designers and die makers). For an updated list, please check file format specification.



Embedding interactive 3D object in a PDF using MeshLab and U3D

Visual Computing Group - ISTI - CNR
http://vcg.isti.cnr.it

5th January 2008

A little example of an embedded U3D object in a pdf. The object is a simplified version of a 3D scanned mesh of a Ippolita Sforza's statue sculptured by Francesco Laurana. This pdf was produced with open source tools. The object was converted in the pdf-ready U3D format with MeshLab (http://meshlab.sourceforge.net) and assembled in a pdf with pdfLaTeX and the movie15 package.

1

40 BIM CAD, developed by Graphisoft, Hungary and launched in 1987, first BIM software. Supports 2d, 3d, rendering, BIM, Desktop Publishing and Document Management/Server Support. Now owned by the Nemetschek Group

41 There are several packages for MatLab
http://www.mathworks.com/matlabcentral/fileexchange/25383-matlab-mesh-to-pdf-with-3d-interactive-object
http://www.mathworks.com/matlabcentral/fileexchange/27245-generate-vertices-faces-and-colour-for-U3D-format

42 Their development was promoted by the consortium to facilitate adoption of the format.

MODIFYING (DIGITAL)

Three of the most common uses for the digital models acquired by photogrammetric means are:

- *Bridging with semantic information in environment such as GIS or BIM*
- *Use as structural models for Finite Element Analysis*
- *Use as digital assets for the Creative and Videogame Industry*

Digital Assets for the Creative and Videogame Industry

Out of the above, further information will be provided on the process of optimizing the models for use as digital assets, since the workflow entailed can be of broader use and interest for the post-processing of models regardless of purpose of use.

Furthermore, it is of increased interest, since the introduction of photogrammetry to the realm of 3d modelling for the creative industry happens to coincide with the relatively new “trend” of “subtractive” modelling, also termed as “digital sculpting”. Digital sculpting produces models which share many basic common traits with models acquired by photogrammetric means. Thus, a great depth of knowledge cultivated from another field of activity about the post-processing of models can be directly attached to the photogrammetric workflow.

Photogrammetric post-processing

The 3d models that are generated by the photogrammetric workflow typically have no regard for model efficiency and need to undergo an optimizing process in order to make them efficient for use in the rendering pipeline. Common optimization issues include mesh size decimation, polygonal unit management (‘‘quads’’ vs. triangles, non-manifold geometry, etc.), edge placement/‘‘flow’’ of polygons, texture sizes, etc.

There is a lot of post-processing that needs to take place to transform a model acquired by photogrammetry into a digital/videogame asset suitable for real-time rendering.

«... it needs to be cleaned up, patched, textured, and processed»

Common issues:

1. Mesh’ resolution by far exceed the size limit for practical application in a 3D game world.

“the outcome is many times over the limit of acceptable polygon size”

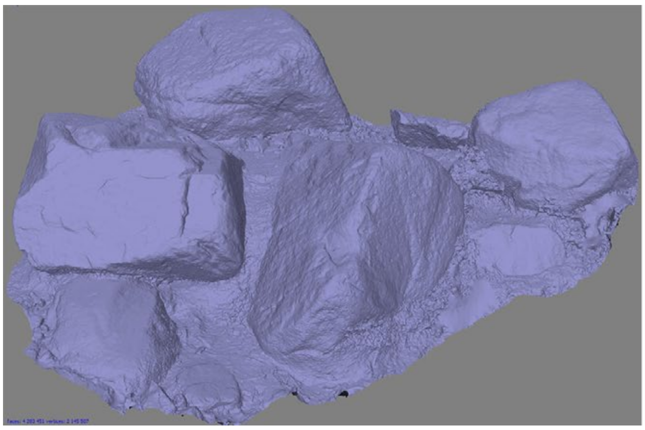
2. The layout of the textures on the image file is unorganised and thus non optimized with regards to image file size.

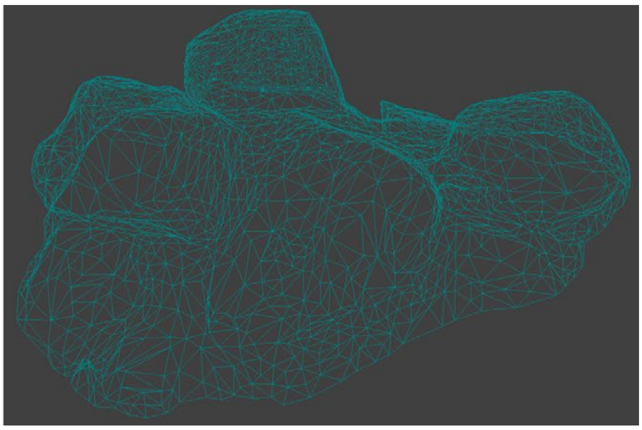
«tight texture coordinates (UVs) to maximize the percentage of used space within the texture»

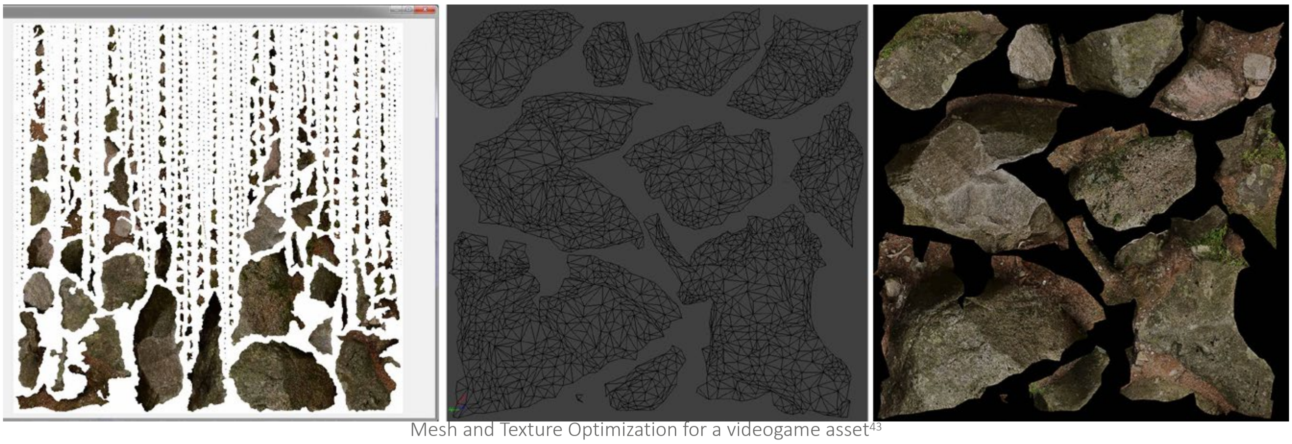
3. Different levels of detail of the model may be needed so that it can be rendered more efficiently if it’s relatively small or in the distance.

Process

- Decimation (from high- to low-poly mesh)
- Retopology
- UV Mapping
- Texture Optimizing



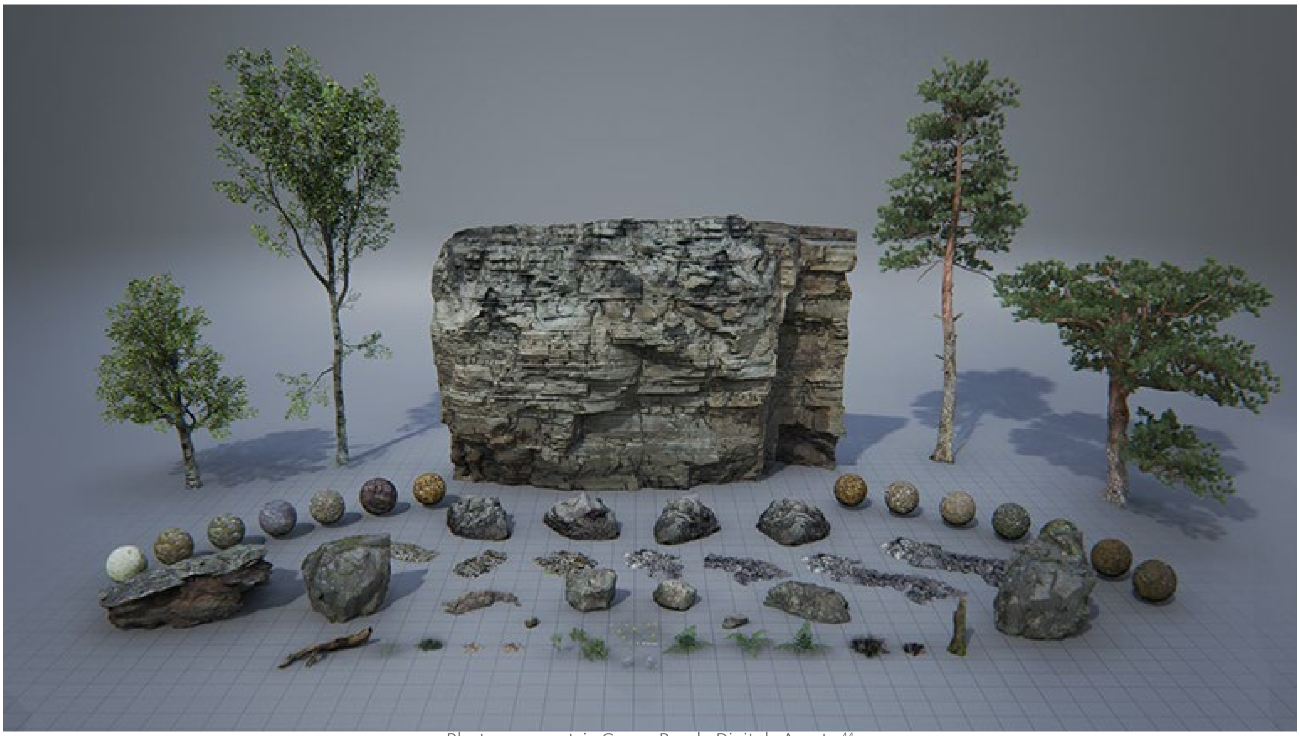




Mesh and Texture Optimization for a videogame asset[43]

Photogrammetric Documentation of Instance or of Class?

Even if accurate documentation of a prototype is not the goal, photogrammetric documentation can still be preferable to 3d modelling/digital sculpting from scratch. Working on optimizing a pre-sculpted model can be more productive, since it allows the user to focus entirely on issues of edge placement, edge flow, and efficient geometry.



Photogrammetric Game-Ready Digitals Assets [44]

Photogrammetry for Videogame assets

Various videogames have already employed photogrammetry for the creation of digital assets: faces, bodies, buildings, objects, locations. Well known titles include[45] Metal Gear Solid V: The Phantom Pain by Kojima Productions, War Thunder by Gaijin Entertainment, Halo 4 by 343 Industries, Cyberpunk 2077 by CD Projekt RED, The Talos Principle by Croteam, Ryse: Son of Rome by Crytek and The Vanishing of Ethan Carter by The Astronauts and Rustclad by Skull Theatre.

Of all the above, it is interesting to make some comments on two (very different) showcases of videogame asset development with a photogrammetric workflow:

43 http://www.theastronauts.com/
44 https://www.unrealengine.com/blog/imperfection-for-perfection
45 https://en.wikipedia.org/wiki/PhotoScan#

I. Rustclad[46], by “Skull Theatre”, a design team of 4.

- Practical argumentation on the use of photogrammetry

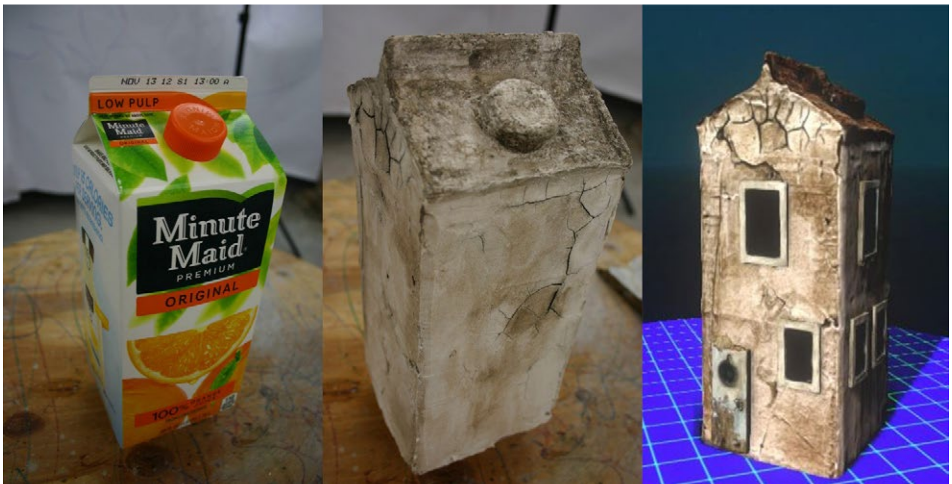
The team presents reasons of monetary cost (affordability) and lack of traditional 3d modelling expertise to support choosing photogrammetry instead of original 3d modelling:

- There is a claim that 3d modelling software is too expensive/off-budget for a small indie creative studio. Although true in the past, this is no longer a valid/strong argument, since the international community is actively developing and supporting open source software that is powerful enough for professional quality results/creations/works, such as “Blender[47]”.
- There is another claim that high expertise is needed for modelling, UV-wrapping and texturing for a videogame. This fact is also true, but the post-processing of photogrammetrically-produced models and their introduction in the game engine requires just as much expertise and skill, albeit of slightly different type.

- Artistic value of photogrammetry

«You can now fall back on more classical art skills like sculpture and painting and work with your hands again».

The uniqueness of the way that this studio has incorporated photogrammetry lies in the fact that all their settings have been inspired by the real world and plunged directly into the 3d virtual space or hand crafted by them. In their art, thus, photogrammetry acts as a pathway to unite two «worlds» - to transgress the boundaries.



Creation Process of digital Videogame assets for Rustclad: ready-made > handcraft > digital model

Aesthetic Outcome: all natural forms have been derived from a photogrammetric procedure[48]

46 Rustclad is still under development. http://www.rustclad.com/

47 https://www.blender.org/

48 https://skulltheatre.files.wordpress.com/2014/09/screenshot31.jpg?w=600&h=337

II. The Vanishing of Ethan Carter, by independent polish studio "The Astronauts"

"The Vanishing of Ethan Carter" is a first person exploration adventure game in the same spirit as "Dear Esther" and "Gone Home".

- "The element of reality"

The art director/producer of this team stresses the visual importance of tiny details on real physical objects, that denote signs of use and weathering- these details appear in a seemingly random, but in essence very meaningful way.

"So much detail, so many intricacies, but most importantly, all of them just make deep sense."

These patterns are very hard to mimic by manual modelling, since as the director put it «the graphics artists' brains don't care about the conscious analysis of reality».

«Assets are no longer simplistic approximations of reality- they are reality»

With photogrammetry, this impression of "materiality" is attained without the need to master and emulate physical laws and effects. To make the most out of this benefit, the team chose to shoot even whole locations/physical formations (forest, rocks, caves, etc.) and not only isolated objects.

What makes this project unique, is the fact that in the final videogame environment, the acquired models of "real" objects are mingled with traditionally hand-modeled ones that all the tell-tale signs of "digitality". The feeling of the videogame space thus created is neither a plastic dream, nor a photo-realistic documentary. As the art director stated:

«The world needs to feel right- not real.»

This in itself it is an uncommon artist statement with theatrical overtones, which makes excellent use of the traits of photogrammetry, going one step further than simple, straight documentation and implementation.

The Vanishing of Ethan Carter: Mingling reality/image-based models with hand-modeled ones

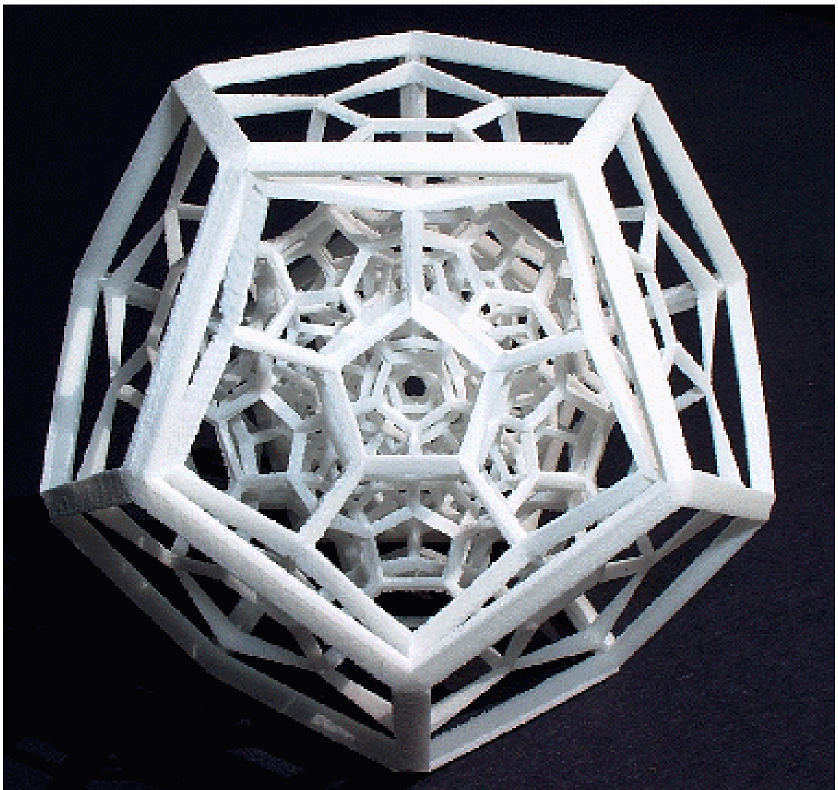
RE-CREATING (PHYSICAL)

3d printing

In order to transform a digital 3d CAD file into a physical object, the most versatile and “natural” production method is **additive manufacturing** (as opposed to subtractive manufacturing). Additive manufacturing denotes the creation process of an object/volume by adding multiple “fusable” material layers, one on top of another, with each layer’s contour representing a horizontal “slice” of the desired object. The additive manufacturing process draws straight from adequately prepared, digital, 3d object models as data input to control the 3d printer’s mechanical actions.

Slicing: from digital to physical[49]

Additive manufacturing is an excellent way for the accurate and fast creation of complicated/demanding geometry in various scales and out of various materials. It has been an important breakthrough in the organization of the production process and its full results are still unfolding. Many have termed the additive manufacturing technology as “disrupting”, since it has the potential to up-turn established norms and expand the capabilities of a market. Its primary use for the time being is for **rapid prototyping**[50] (RP) and any other task of similar nature. Thus, it allows the successful creation all types of **unique & educational 3D objects**: topological, algebraic, molecular, crystal, anatomical, or historical models. Most impressive are cases where traditional manufacturing would be difficult to near-impossible.



120 Cell, from G.Hart’s Mathematical Model Museum, STL files available[51]

49 http://hotmess3d.com/about-3d-printing

50 Rapid prototyping is a group of techniques used to quickly fabricate a scale model of a physical part or assembly using three-dimensional computer aided design (CAD) data. Nowadays, AM is also used to manufacture production-quality parts in relatively small numbers if desired without the typical unfavorable short-run economics.

51 http://www.georgehart.com/rp/rp.html

3d Printing Technologies

Various methods have been developed that share the same common notion of "layering". The can be subdivided in the following categories:

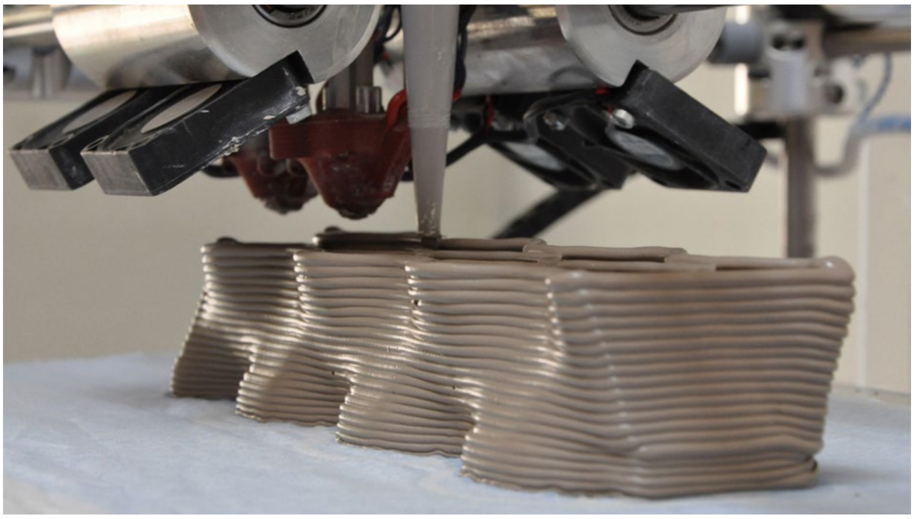
- Selective Light Curing/Polymerization
- Selective Laser Sintering (SLS)
- Fused Deposition Modelling & Fused Filament Fabrication (FDM / FFF)
- Drop-on Powder Deposition
- Pattern Lamination (Bond-first/Cut-first)

T. rex Head: 1:10 scale selective laser sintering print of photogrammetric model[52]

3d printing materials

The above technologies can handle a wide range materials, (including plastic, metals, (food safe) ceramics, paper, etc.) in a variety of states (powder, filament, pellets, granules, resin) and are able to cover a wide range of needs. The most commonly available technology for the consumer market, though, is the **Fused Deposition Modelling** system (**FDM/FFF**), which uses filaments out of thermoplastic material, such as:

- ABS (Acrylonitrile Butadiene Styrene)
- PLA (Polylactic Acid) > biodegradable
- PVA (Polyvinyl Alcohol) > water-soluble, in various diameters, colours, length and physical properties.



Building structural bricks out of clay with FDM[53]

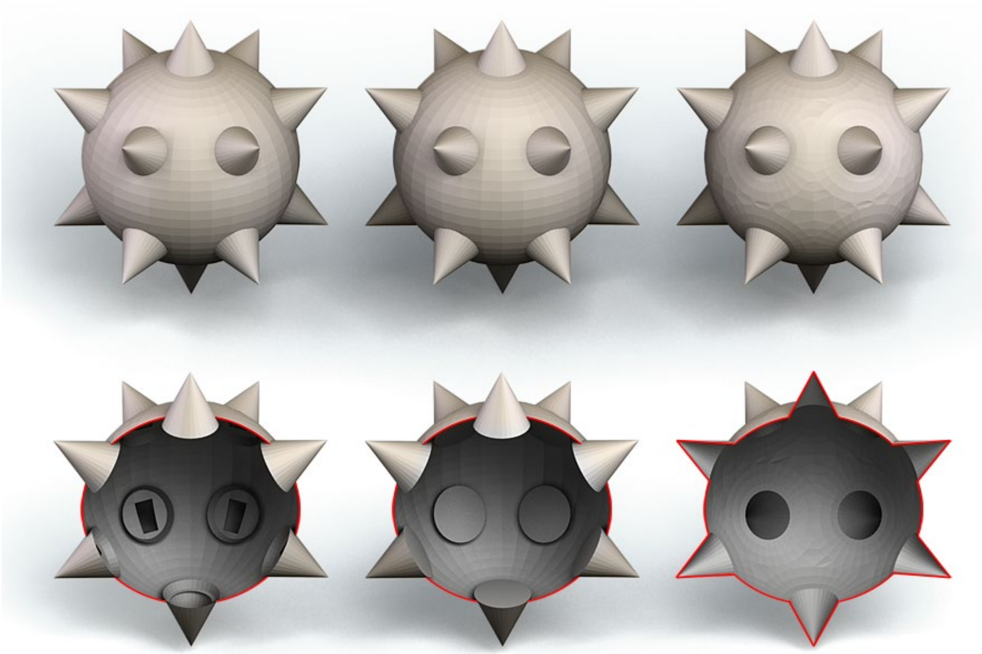
52 https://dinosaurpalaeo.wordpress.com/2015/11/11/tristan-3d-printing/
53 http://buildingbytes.info/

What are the challenges for model preparation?

A model intended for 3d printing has different performance requirements than one intended for digital use. "Clean" geometry, smoothed meshes, integrity and statical/physical soundness are imperative. Photogrammetry (as well as laser scanning) can create models with background, holes, noise, extreme density, etc.

A simple checklist for the preparation steps of a model for 3d printing follows:

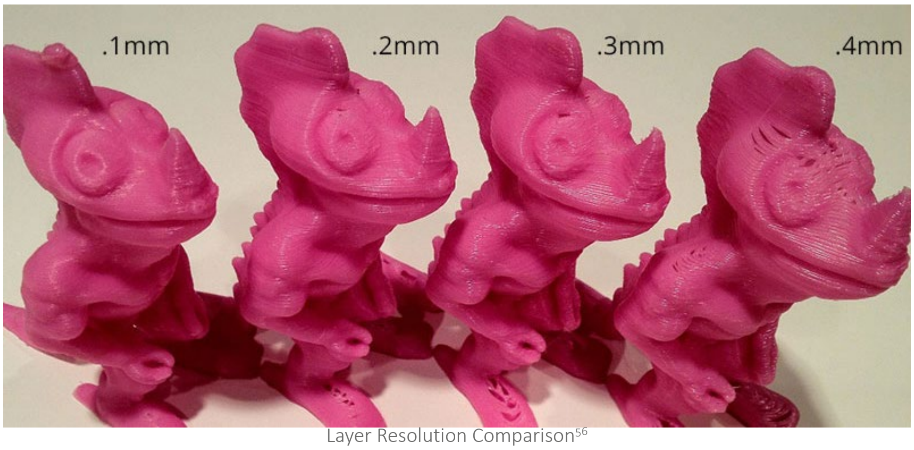
- *Removing background:* The output mesh from a photogrammetric workflow does not set apart the object from each surroundings. Manual editing to "cut" it out is involved.
- *Cleaning up any internal geometry & artifacts:* In case the model creation process has Only the external surface
- *"Water-Tight" mesh:* A very important prerequisite for 3d printing is a fully closed external surface of the model. The term "water-tight" is a slang term to refer to the closed boundaries of the shape. Filling gaps/closing holes of the model can be manual or automated. Also note that some printing service agencies, such as Shapeways, offer automated model closure. If intended
- *Refining the resolution of the mesh:* The mesh' size/resolution depends on the photo-capturing process and the photogrammetric processing of the images. The resolution of the 3d printing model though, depends on the mechanical setup of the equipment in terms of the minimum movement of the stepper motor[54], mainly in Z axis (layer). Thus, the model needs to be decimated according to the resolution of the 3d printer.
- *Smoothing:* Texture details too fine for the resolution of the printer will be lost, as well as too subtle curvature changes of the surface. Smoothing the model out to the desired resolution is advised for preview & better control of the result.
- *Reinforcing:* Note areas that are sensitive in terms of physical load-bearing, as well as connections of parts that seem fragile, such as protruding appendages. Manual editing of the mesh to reinforce these vulnerable areas (by thickening their width, etc.) may be needed.
- *Normal Orientation:* Check that normal vectors are all facing outwards from the external surface of the model.



Example of creating a 3d printing-ready, watertight mesh (from left to right)[55]

A common open-Source software for model preparation for 3d printing is Netfabb.
http://www.netfabb.com/explained.php

54 A motor with a gear-shaped rotor that allows for very precise movement and the ability to be stopped at very precise points without creating backlash.
55 http://support.ponoko.com/entries/20217167-Creating-Watertight-Meshes-for-3D-printing



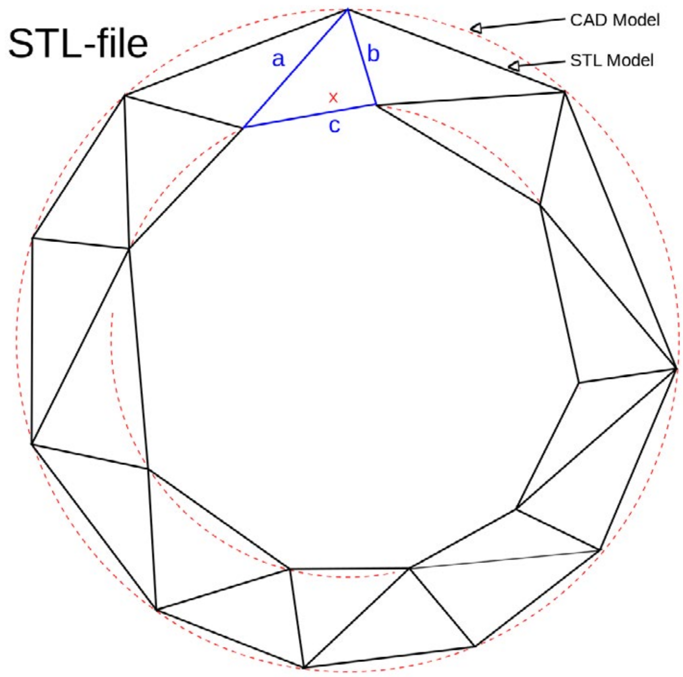
Layer Resolution Comparison[56]

Converting meshes into printable formats

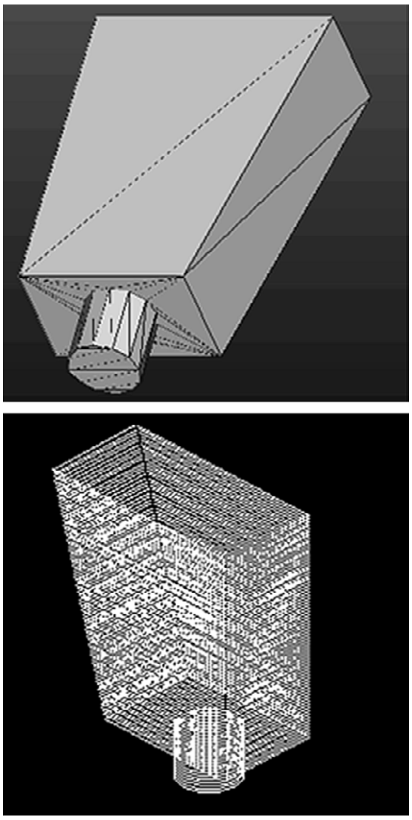
In order to print a model, converting into a readable format is necessary. The established file formats for 3D printing are **STL** and **VRML**. Other commonly used formats are OBJ, X3D, DAE or Collada. STL stands for **stereolithography** and has become the Rapid Prototyping industry's **de facto standard data transmission format**. It is supported by many 3d modelling software, but in some cases a plug-in may be needed to export the model files.

An STL file is a triangular representation of a 3-dimensional surface geometry. The surface is tessellated or broken down logically into a series of small triangles (facets). Each facet is described by a perpendicular direction and three points representing the vertices (corners) of the triangle. These data are used by a slicing algorithm to determine the cross sections of the 3-dimensional shape to be built by the printer.

Due to the different description method of geometry employed by the STL file format, alterations on the original mesh geometry are to be expected- in specific in organic freeforms. The following sketches illustrates the way geometry is represented in STL format:



STL to CAD file format[57]


Differences in geometry representation between CAD file and STL file[58]

56 http://tobuya3dprinter.com/3d-printing-resolution-structural-strength/
57 https://commons.wikimedia.org/wiki/File:The_differences_between_CAD_and_STL_Models.svg
58 Ren C. Luo & Jyh-Hwa Tzou, "Development of a LCD Photomask Based Desktop Manufacturing System", 2010

3d Printing Options

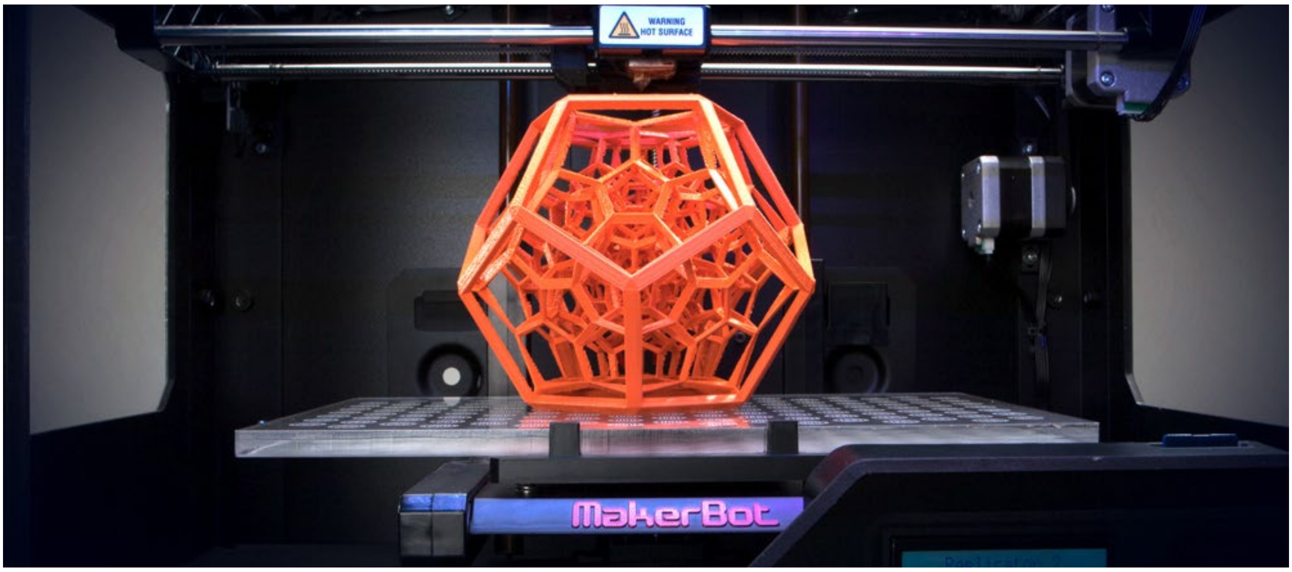
Depending on the specifications of the desired 3d print, the task can be handed over to a devoted agency or performed by own means with desktop 3d printing machines.

- Desktop 3d Printers

Affordable desktop printers for the time being limit themselves to a large extend to the FDM/FFF technology, as stated, but are rapidly developing in terms of investment cost, mechanical durability & refinement, as well as available materials and versatility. Apart from **commercial** solutions, there is a great momentum at the development of **open-source DIY alternatives**, with the RepRap community as the most notable example.

Short List of Commercial 3d printers

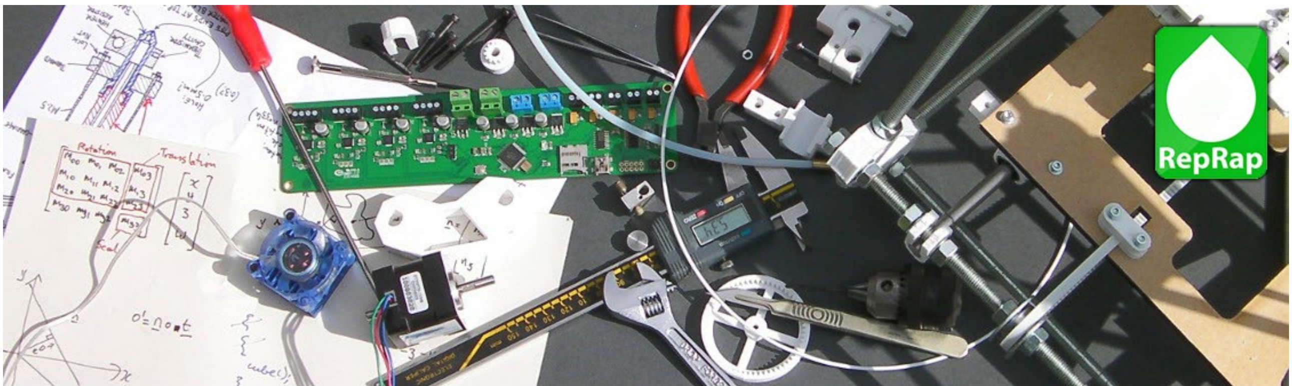
Afinia	Printrbot
FlashForge	Up!
Makerbot	XYZPrinting
MakerGear	Ultimaker
Mbot 3D	DeltaWASP



Example of commercial, desktop ed printer: Makerbot[59]

Short List of DIY printers

Rostock	Prusa
Mendel	Ultimaker



RepRap community develops self-replicating models and distributes software and hardware instructions[60]

59 http://www.makerbot. com/
60 http://reprap.org/

- 3d Printing Services

A more versatile alternative to investing in a privately owned 3d printer is participating in a fabricators' community either in **physical** or in **digital space**.

Physical Meeting Places / Hubs:

A **makerspace**[61], also called a hackerspace, is a physical location containing computers with software, hardware, and fabrication tools for members or for public use. Hackerspaces can be community-operated, such as FabLab[62].

FabLab Asia[63]

Online Printing Services:

Web-Places such as these offer individual 3d printing services with a variety of technologies and materi-als, including shipment. Some services also offer technical support for the optimization of the models. Most also act as forums for exchange of opinions & know-how and as marketplaces how buying and selling digital models or their 3d prints.

sculpteo shapeways makexyz

Shapeways	http://www.shapeways.com/
Sculpteo	www.sculpteo.com/en/
Ponoko	https://www.ponoko.com/
MakeXYZ	v
You3dit	https://www.you3dit.com/

** Finding Local 3d Services online*

WebService 3d Hubs locates the closest affiliated makerspace/commercial 3d printing service based on given location:

3D HUBS

www.3dhubs.com

61 https://makerspace.com/
62 http://www.fabfoundation.org/fab-labs/what-is-a-fab-lab/
63 http://fablabasia.net/

SECTION D)
IN THE END

CONTENTS

CONCLUDING REMARKS

The idea for the creation of this handbook has been the recognition that the science of photogrammetry enters a **new “era” of openness and increased efficiency**. This offers high potential for the **popularization** of photogrammetry and its **familiarization** with a wider user group. The challenge therein lies realising this potential. To this purpose, two elements are deemed necessary:

- the need for i**nformation of a wider audience** about the capabilities of the photogrammetric methods &
- **training of new users** in both practical and theoretical aspects

For this process to take place effectively, the new potential “**user groups**” need to be identified in terms of their profile, so that suitable **educational material and methods** can be prepared based on the particular **background** and **demands**.

This handbook has been an effort to put together introductory material having an “unknown” reader in mind, who might -or might not- be familiar with some of the many skills and concepts involved in a photogrammetric project. The challenge has been both in terms of content and in structure of the handbook: selecting the **scientific disciplines** that should be involved, choosing the particular **aspects of each most related** to photogrammetry and presenting the material without over-simplification but also without demanding a particular set of pre-established knowledge. The most important statement that this handbook has to make is that **theoretical & practical knowledge** should be combined, regardless of the automation capabilities of the method. This combination can lead to fast development in terms of expertise for the new users and help to avoid **over-dependency on automation** which by itself is not able to guarantee adequate results.

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- http://culturalheritageimaging.org/

3d Coform

- http://www.3d-coforom.eu/
  Heritage Together Project
- http://heritagetogether.org/?lang=en
  3d Archeo Lab
- http://www.3d-archeolab.it/
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- http://www.tested.com/art/makers/460142-art-photogrammetry-how-take-your-photos/
  Tested Ezine Article: 3d Printing Photoscanned Item Article
- http://www.tested.com/tech/concepts/460516-art-photogrammetry-replicating-hellboys-samaritan-pistol/
  Blog about Image Based 3d Modeling
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- http://wedidstuff.heavyimage.com/index.php/2013/07/12/open-source-photogrammetry-workflow/
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- http://blog.sketchfab.com/post/121838008009/how-to-set-up-a-successful-photogrammetry-project
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- http://www.pgrammetry.com/forum/index.php
  3dDIYScan Forum: Photogrammetry Topic
- http://www.virtumake.com/forum/viewforum.php?f=40

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- http://ir-ltd.net/
  Ten24
- http://ten24.info/
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- http://www.scanlab.ca/
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- http://www.alexxhenry.com/motion/

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- http://www.theastronauts.com/2014/03/visual-revolution-vanishing-ethan-carter/
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USEFUL ABBREVIATIONS[1]

ADC	analogue-to-digital converter
AGC	automatic gain control
ASCII	American Standard Code for Information Interchange
ASPRS	American Society for Photogrammetry and Remote Sensing
BRDF	bidirectional reflection distribution function
CAAD	computer aided architectural design
CAD	computer aided design
CAM	computer aided manufacturing
CCD	charge coupled device
CD-ROM	compact disk – read-only memory
CID	charge injection device
CIE	Commission Internationale de l'Éclairage (International Commission on Illumination)
CIPA	Comité International de Photogrammétrie Architecturale (International Committee for Architectural Photogrammetry)
CMM	coordinate measurement machine
CMOS	complementary metal oxide semi-conductor
CT	computer tomogram, tomography
CTF	contrast transfer function
DCT	discrete cosine transform
DLT	direct linear transformation
DMD	digital mirror device
DOF	degree(s) of freedom
DRAM	dynamic random access memory
DSM	digital surface model
DTP	desktop publishing
DVD	digital versatile (video) disk
DXF	autocad data exchange format
EP	entrance pupil
E'P	exit pupil
EPS	encapsulated postscript
FFT	full frame transfer or fast Fourier transform
FMC	forward motion compensation
FOV	field of view
FPGA	field-programmable gate array
FT	frame transfer
GIF	graphic interchange format
GIS	geo(graphic) information system
GPS	global positioning system

1 Luhmann, T. et al, "Close Range Photogrammetry", 2006, Whittles Publishing

HDTV	high definition television
IEEE	Institute of Electrical and Electronic Engineers
IFOV	instantaneous field of view
IHS	intensity, hue, saturation
IL	interline transfer
INS	inertial navigation system
ISO	International Organisation for Standardization
ISPRS	International Society for Photogrammetry and Remote Sensing
JPEG	Joint Photographic Expert Group
LAN	local area network
LCD	liquid crystal display
LED	light emitting diode
LoG	Laplacian of Gaussian
LSM	least squares matching
LUT	lookup table
LW/PH	line widths per picture height
LZW	Lempel-Ziv-Welch (compression)
MOS	metal oxide semiconductor
MPEG	Motion Picture Expert Group
MR	magnetic resonance
MTF	modulation transfer function
PCMCIA	Personal Computer Memory Card International Association
PLL	phase-locked loop or pixel-locked loop
PNG	portable network graphics
PSF	point spread function
REM	raster electron microscope
RGB	red, green, blue
RMS	root mean square
RMSE	root mean square error
RPV	remotely piloted vehicle
RV	resolution power
SCSI	small computer systems interface
SLR	single lens reflex (camera)
SNR	signal-to-noise ratio
SPIE	The International Society for Optical Engineering
TIFF	tagged image file format
TTL	through the lens
TV	television
USB	universal serial bus
VLL	vertical line locus
VR	virtual reality
VRML	virtual reality modelling language

APPENDIXES

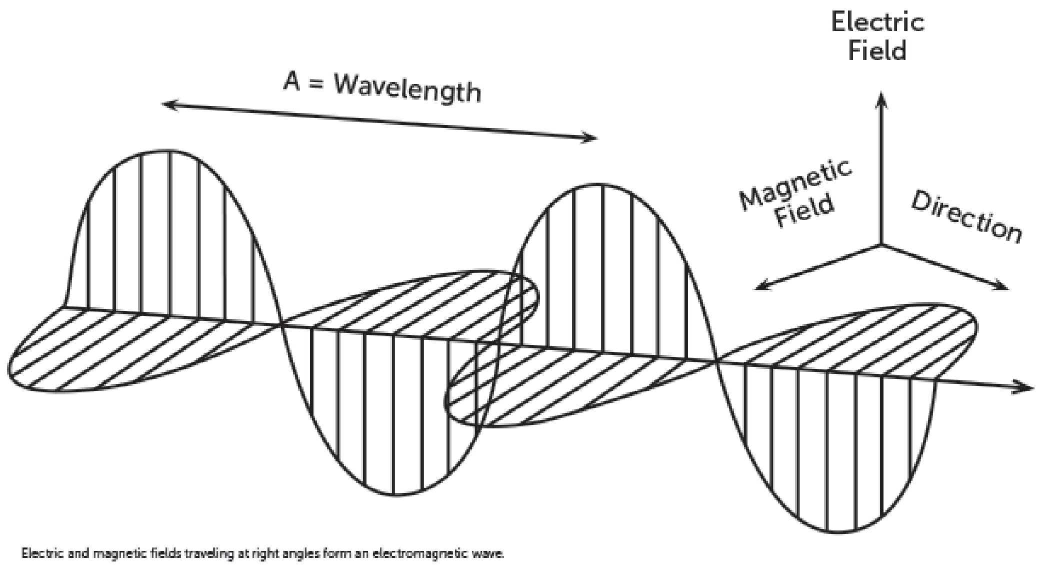
ON THE NATURE OF LIGHT

keywords: <EMR radiation, light-ray, geometrical optics, energy equilibrium, point light-source (divergent light-ray bundle), directional light (light source at infinity=parallel light rays), specular/diffuse reflection>

The implication of light is evident in the word “photography”[2] (φῶς + γράφω = light + drawing). Given its significant role at such a primary level, it is useful to understand a few basic properties of light.

Electromagnetic radiation

Light, in its most general approach, is electromagnetic radiation (**EMR**): it consists of an electric and a magnetic wave, travelling space perpendicular to each other and to the direction of motion (transversely).



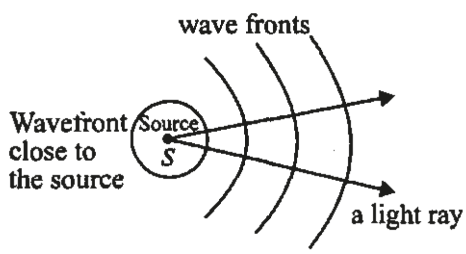
transverse EM waves to traveling direction[3]

Waves

The most defining properties that characterise a wave and its behaviour are its wavelength λ, amplitude *A* and frequency *f*.

Rays

A light-ray can be described as the perpendicular line to a series of successive wave fronts specifying the direction of energy flow in the wave.

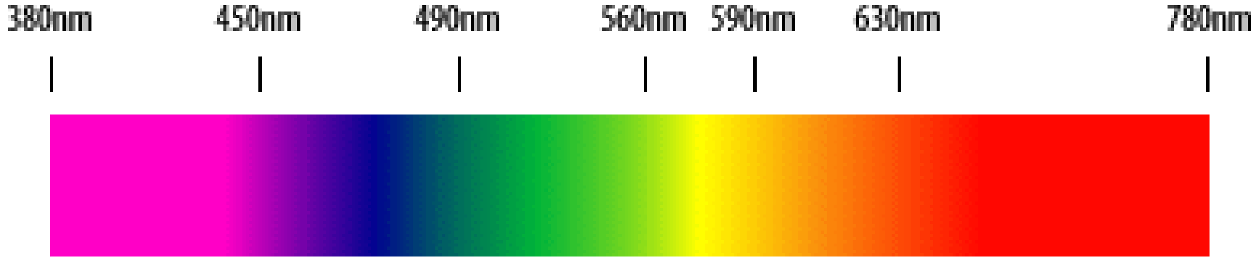


Wave front and Light Ray originating from source[4]

2 Heliography, photogeny and daguerreotypy were initially also proposed as names.
3 http://www.doncio.navy.mil/CHIPS/ArticleDetails.aspx?ID=4519
4 https://www.ualberta.ca/~pogosyan/teaching/PHYS_130/images/rays.png

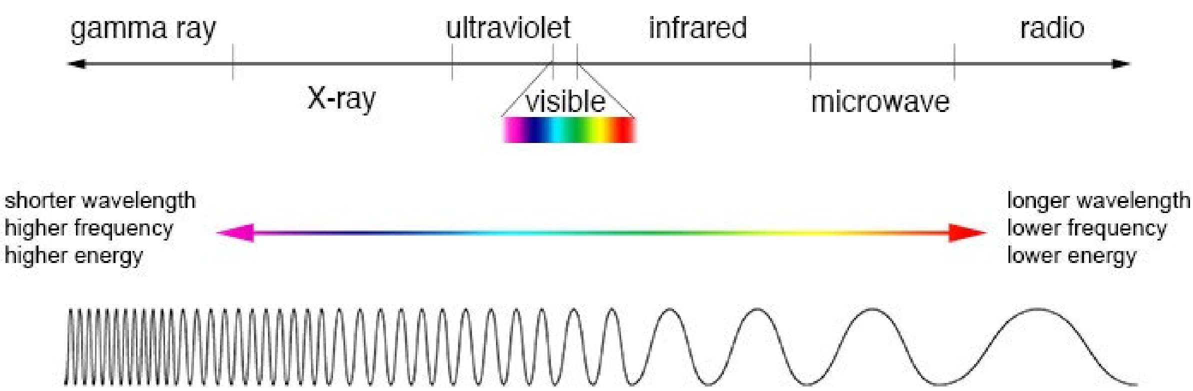
Visible Light

Light is only one of the expressions of electromagnetic radiation. In specific, it is only a small fraction of the electromagnetic spectrum, covering an area of wavelengths from approx. 380 to 780 nm.



colour progression according to wavelength[5]

Light is of the same "stuff" as non-visible radiation, such as radio waves and gamma rays. It's unique property that sets it far apart from the rest of the spectrum and so high in our priorities, is the fact that the human being (as many others) is evolutionary equipped with biological sensors to experience light as a stimulus. This gives birth to the sense of sight - at least in terms of external, primary input. For other spectral ranges of radiation, specifically-devised, man-made sensors need to be developed!



The full length of the electromagnetic spectrum - The electromagnetic spectrum can be sliced up into discrete segments of wavelength ranges called bands, also sometimes referred to as a channel.[6]

Sources of Light/Light emission

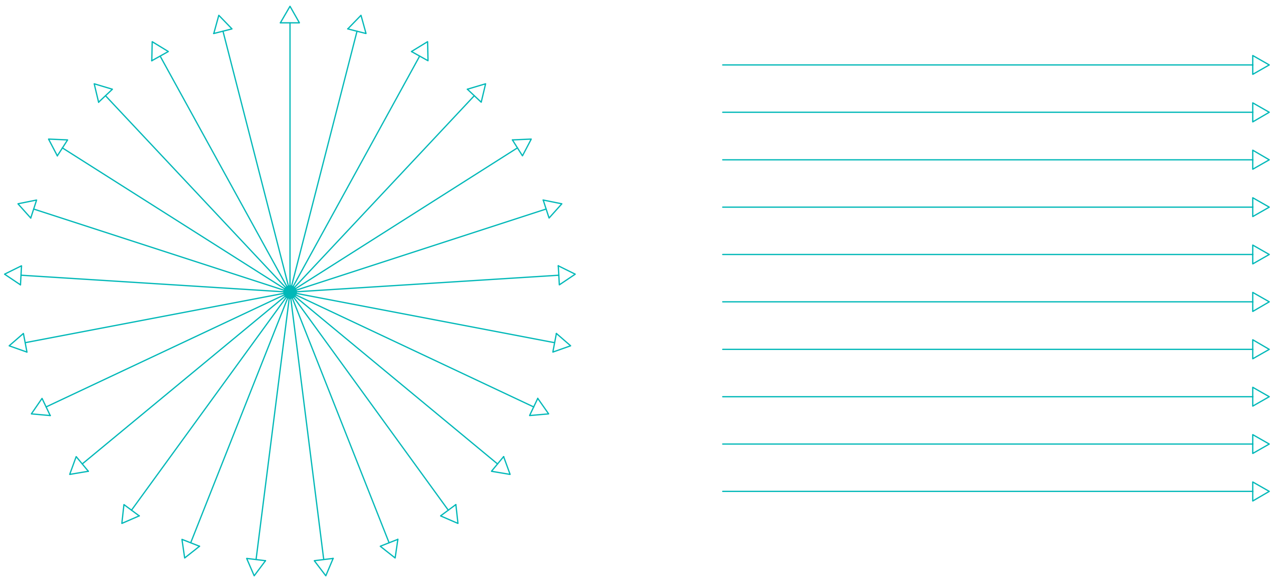
Light is produced by many methods, most common of which is the method of incandescence: the emission of light from "hot" matter (T > 800 K[7]). Experienced in daily life, our main thermal light source is the sun, whose emission has only a 44% percentage of visible light in Earth's atmosphere.

Another light sources can be explained with the method of luminescence: when the emission of light comes from excited electrons that fall to lower energy levels. Whatever the case, a light source can described by the pattern of wavelengths that it emits. The graphical display of this distribution is called a spectral curve. Other than that, the shear "amount" of energy emitted is also a descriptive factor. The field of detection and measurement of light energy is called radiometry.

5 www.rmutphysics.com
6 imagine.gsfc.nasa.gov
7 Kelvin is a temperature scale designed so that zero degrees K is defined as absolute zero, a hypothetical temperature, all molecular movement stops. The size of one unit Kelvin is the same as the size of one degree Celsius and K = C + 273.16°

Light source at infinity

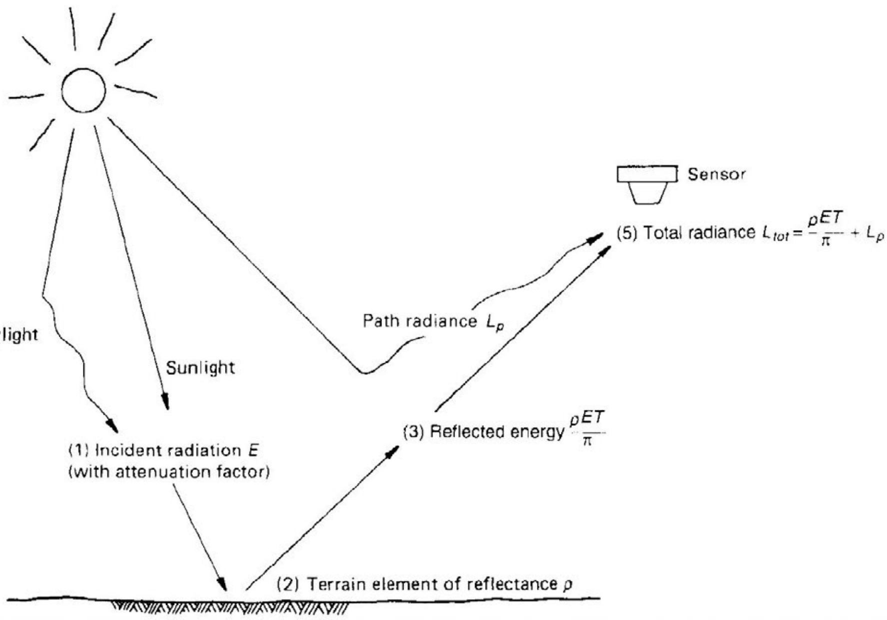
We model the transmission of light-rays from a nearby point light-source as radiating in all directions in space(divergent light-ray bundle). If the light source is regarded as if at infinite distance from the target, we model the transmitting light rays as parallel (directional light).



Nearby Point Light-Source radiating Light & Parallel Light Rays from Light-Source at infinity[8]

Interaction with matter & Equilibrium

Light, emitted from light sources, travels in vacuum & space and finally falls on matter. There it becomes partly absorbed and partly reflected. The selective absorption of wavelengths is also the basis for the object’s colour. EM energy is also emitted from objects, but in wavelengths that are not in the visible spectrum (thermal)- if visible, the object is termed as a light source.



Schema of Light energy from sun source traveling space and interacting with matter[9]

Energy Equilibrium : the amount of Incident energy is equal to the amount of Reflected, absorbed and transmitted energy[10]

8 http://math.hws.edu/graphicsbook/c4/point-vs-directional-light.png
9 Lillesand T. et al, “Remote Sensing and Image Interpretation,7th Edition”, Wiley, 2015
10 ibid

Optics

The study of light and the interaction of light and matter is termed Optics. Based on the aspects involved, we can make a distinction between:

- **Geometrical Optics**, which treats the propagation of light in space as rectilinear **light-rays**
  &
- **Physical Optics**, which deals with the **wave-like** behaviour of light.

Geometrical Optics

Geometrical optics can be viewed as an approximation of physical optics, which applied to large scale effects, meaning when the wavelength of the light is much smaller to the size of the matter with which it interacts (i.e. light passing through lenses or reflected on mirrors). It follows then, that physical optics can be employed to describe effects that deal with small-scale interactions, such as the passing of light through very small openings.

Phenomena that fall under geometrical optics and use the concept of the light-ray are the most "common" ones and have been noted since antiquity. These are:

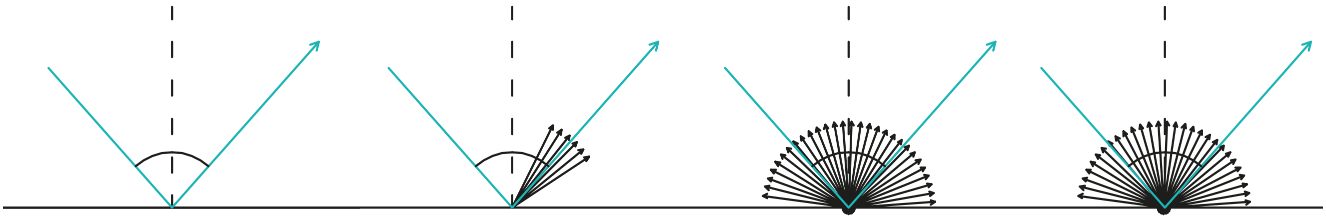
- **Reflection** (and its types) &
- **Refraction**.

Phenomena that are interpreted by the wave aspect of light include:

- **Interference**,
- **Diffraction** &
- **Polarization**.

Reflection

Depending on profile of the surface, the optical result of reflection can vary. On one extreme, there is specular reflection (mirror/very flat surfaces) where the incident angle is equal to the reflection angle and on the other, diffuse reflection (rough/textured surfaces) where the light is redirected in a wide range of directions.

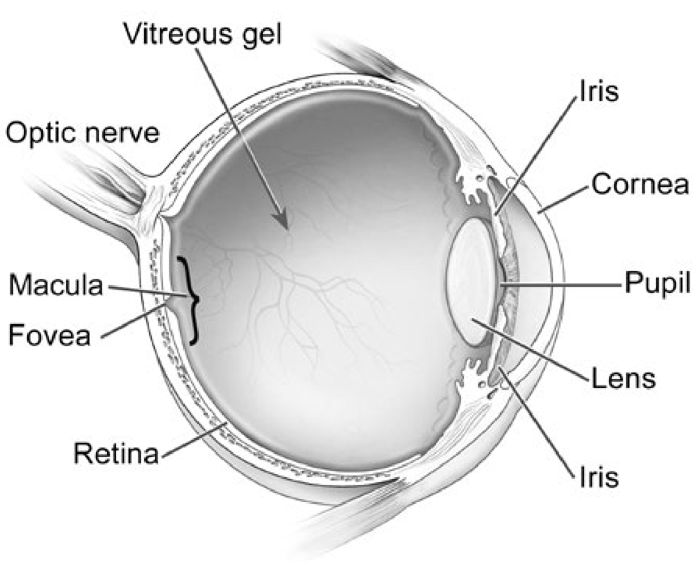


Summary

For the purpose of photogrammetry, we deal with geometrical optics about the movement of light in space and in specific, we model the interaction of light with matter, aka the visible world around us, with rectilinear light rays originating out of every point of a material object, because of reflection of the incident light-rays emitted by a light source. Every material point in space becomes visible if the originating light ray hits on a light-sensitive sensor/our eyes.

HUMAN VISION

keywords: < Iris, Pupil, Lens, Retina, Photoreceptors, Spatial Resolution, Radiometric Resolution, Field of View, Optical Axis>



The eye’s anatomy[13]

The mechanism of Vision

The eye, the optic nerve & the brain are the components of the biological system that enables to us the sense of vision.

It should be clear that the sense of vision does not “occur” in our eyes[11]. As with the rest of our senses, energy from the surrounding environment -in this case, light- acts as a stimuli on our biological sensor -the eyes- and the resulting information travels through a channel -the optic nerve- to the central processing unit, our brain, where it is interpreted.

The eye as an optical instrument

The human eye is a slightly asymmetrical globe, 2.5 cm in diameter. The design of the human eye as a biological light sensor is not the universal solution for all life species, but it is adapted to offer humans a very important range of evolutionary advantages[12].

Human Eye Anatomy:

- The Cornea, a spherical, transparent dome over the iris. It refracts <focuses> incoming light into the pupil.
- The Pupil, an opening on the iris that allows the light to enter the inside of the eye.
- The Iris, the pigmented surface that surrounds the pupil. It blocks all incident light and regulates the size of the pupil, therefore the amount of incoming light.
- The crystalline Lens[14] (refraction index, 1.4). It focuses incoming light rays on the retina.
- The Vitreous, the liquid interior of the eye, with refraction index of 1.33 (equal to that of water).
- The Retina, the interior spherical surface of the eye, tiled with light-sensitive cells (see more below)
- The Macula, the area on the centre of the retina. It has a denser distribution of photoreceptors than the periphery.
- The Fovea[15], a small depression on the surface of the macula with the highest density of photoreceptors[16].
- The Optic Nerve, «a bundle of one million nerve fibres», where the electrical impulses generated on the retina are gathered and shipped to the brain for interpretation.

On the Retina: Photoreceptors

11 Although vision and sight are considered synonyms in daily use, we can point to a fine distinction between them. «Sight» denotes the actual, physical “ability to see“ -to register light and its colours-, whereas «vision» refers to the ability(sense) of sight. Therefore, could state that our eyes are capable of sight and ourselves capable of vision.

12 For example, numerous insects species have composite eyes and are sensitive to ultraviolet, whereas some reptilians are sensitive to infrared. Penguins have a flat cornea that allows for clear vision underwater and are also able to see into the ultraviolet range. On the visual acuity and traits of other life species, see more on comparative visual physiology & functional ecology.

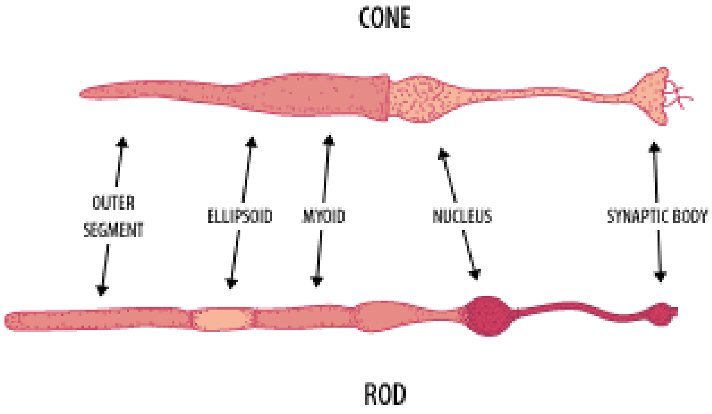
13 healthyeyes/howwesee.asp

14 Also known as “aquula”, the Latin word for “little stream”.

15 Also coming from Latin, meaning “pit” or “pitfall”

16 Approximately half of the nerve fibres in the optic nerve carry information from the fovea.

Photo-receptive cells on the surface of the retina function as our light sensors- they convert light energy into electrical signals. They are divided in two categories: cones and rods. The cones are responsible for colour vision, operate at high light levels and offer sharp, central vision. The rods take over at low luminance, cannot distinguish among colours and offer peripheral vision.



Cone & Rod Cells[17]

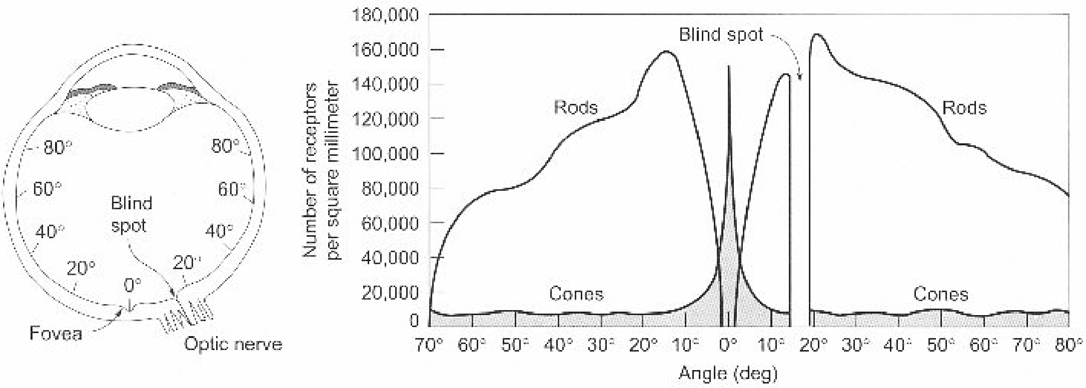
Rods:
- Concentrated on the periphery of the retina & used in peripheral vision
- Due to very high light sensitivity[18], functional in low light conditions, responsible for scotopic vision
- Absence of rods in the foveal region[19]
- Slower to respond, therefore unable to register fast changing images
- «Gray-scale» sensors, no colour distinction[20]

Highest sensitivity to green-blue range of spectrum, responsible for Purkinje effect[21]

Cones:
- Functional under bright conditions
- Most concentrated on the central surface of the retina, the macula, responsible for sharp vision
- Fast registration of stimuli
- Responsible for colour vision
- Occur in 3 Variations, sensitive to different ranges of the spectrum : S(hort)-cones, M(edium)-cones, L(ong)-cones[22]

17 http://dba.med.sc.edu/price/irf/Adobe_tg/colour/vision.html
18 Rods are 100 times more sensitive than cone cells. They can register even a single photon, which explains why «absolute darkness» is rare to experience in normal conditions.
19 This explains why our visual acuity in scotopic vision is very low.
20 This is one reason why colour vision declines in dim light.
21 The Purkinje effect describes the shift of peak luminance sensitivity of the human eye toward the blue end of the colour spectrum at low illumination levels. This also brings about changes to the perception of contrast under different levels of illumination. This observation has led to the adoption of red-hued lights in cases where high visual acuity under low-light conditions is necessary.
22 Cones are responsible for trichromatic colour vision. The final colour signal is composed in the brain- up to now the most common theory for the colour perception mechanism is the colour opponent process.

Distribution of Rod & Cone Cells on the retinal surface: Fovea & Blind spot positions and relation to optic nerve

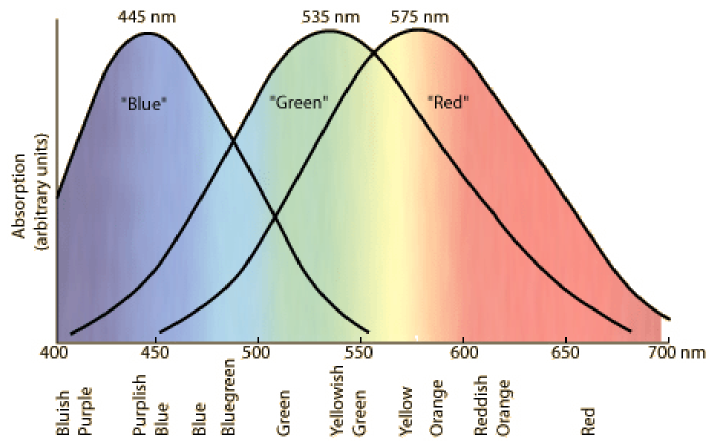


Distribution of rods & cones in the retina[23]

Spectral Sensitivity

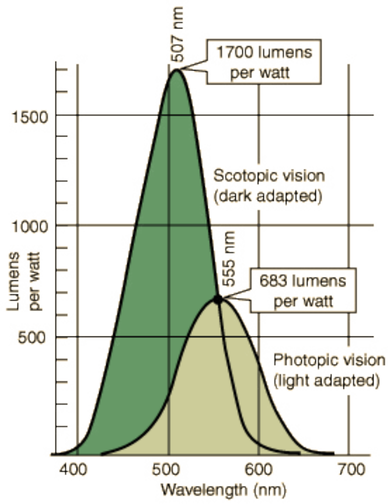
The human ability to detect light is dependent on the environmental luminance conditions. In general conditions, humans have the ability to detect light from a spectral range as low as 380nm up to 800nm with the highest spectral sensitivity at 555 nm.

Distribution Curves of the each cone types’ sensitivity to light-waves (in lighted conditions)



Sensitivity functions of the above chart have been normalized to a value of 1[24]

Distribution Curves of average sensitivity in photopic and scotopic vision



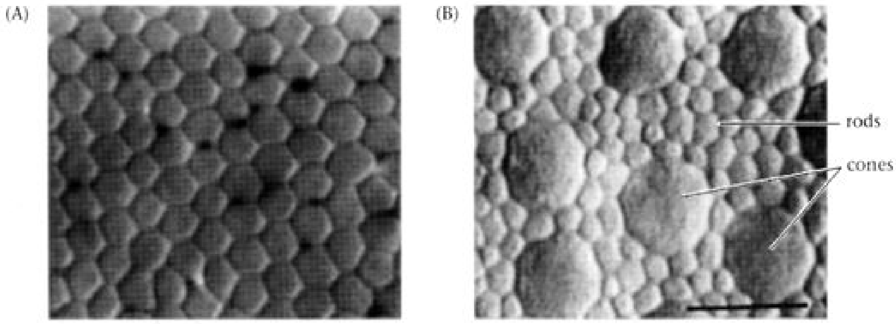
Shift in wavelength peak sensitivity between Scotopic/Dark adapted & Photopic/Light adapted Vision[25]

23 http://hyperphysics.phy-astr.gsu.edu/hbase/vision/rodcone.html
24 http://hyperphysics.phy-astr.gsu.edu/hbase/vision/colcon.html
25 http://hyperphysics.phy-astr.gsu.edu/hbase/vision/bright.html

Cone vision, known as photopic or bright-adapted vision, is most sensitive to green light - relative emission from the sun is also greatest at about this wavelength. Rod vision, also known as scotopic vision is most sensitive to the blue end of the spectrum. At twilight, where little direct sunlight (full spectrum) is available, the available light is caused by atmospheric scattering (Rayleigh effect). This low luminance light is bluish.

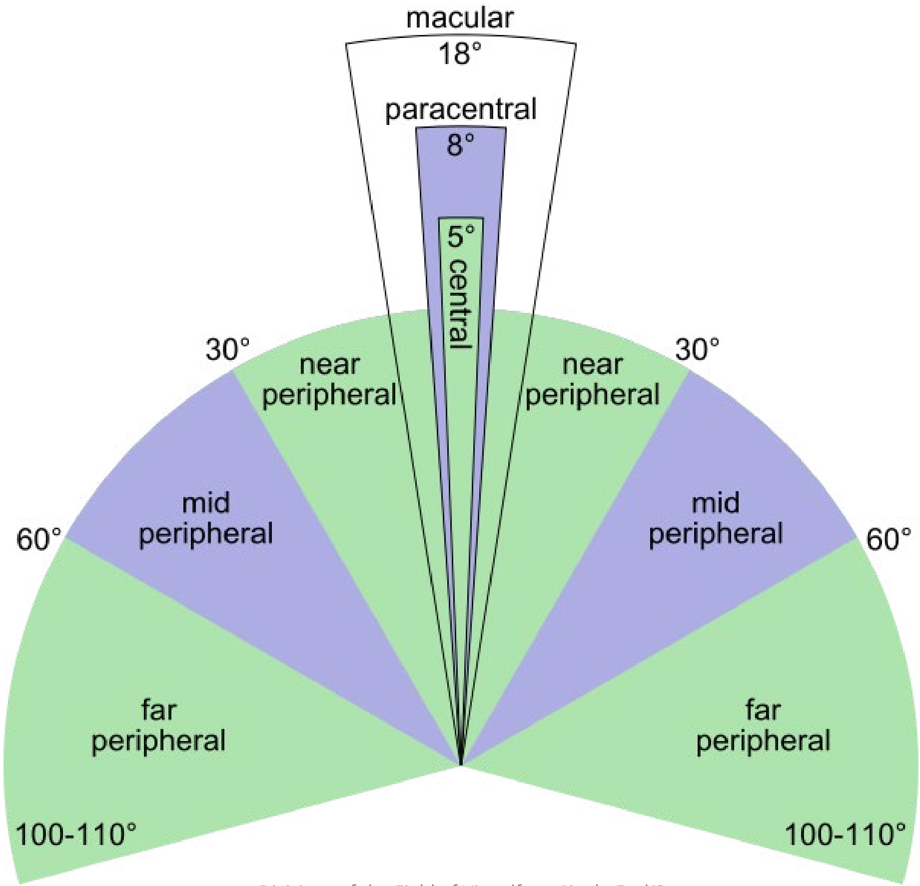
Field of View: Central(foveal) vision - Peripheral vision

The fovea, despite its small size, is a very important element in the design of our eye. It is responsible for our sharp, focused central vision (also called foveal vision). When the eye is fixed on a certain object, it is merely focusing the object on the fovea, where the eye has the greatest spatial resolution.



Hexagonal tiling of cone cells on the foveal region(densest possible formation) & Comparative size of rods to cones[26]

Each eye individually has anywhere from a 120-200° angle of view, depending on how strictly one defines objects as being "seen", which is nearly as wide as a fish-eye lens. The central angle of view — around 40-60° — is what most impacts human perception. This would correspond to a lens with **50mm focal length** lens (on a full frame camera). At the periphery of vision, humans only detect large-scale contrast and minimal colour.



Divisions of the Field of View (for a Single Eye)[27]

26 http://www.cis.rit.edu/people/faculty/montag/vandplite/pages/chap_9/ch9p1.html
27 https://en.wikipedia.org/wiki/Peripheral_vision

Variable Focal Length / Lens Accommodation

The crystalline lens can change its shape by means involuntary muscular contractions from the ciliary muscles, a trait known as **accommodation**. This adjustment effectively changes the power of the lens, i.e. the focal length. This variation allows for clear focusing on objects both near and far. To focus on far objects the lens becomes relatively flat and to focus on nearer objects the lens becomes more curved.

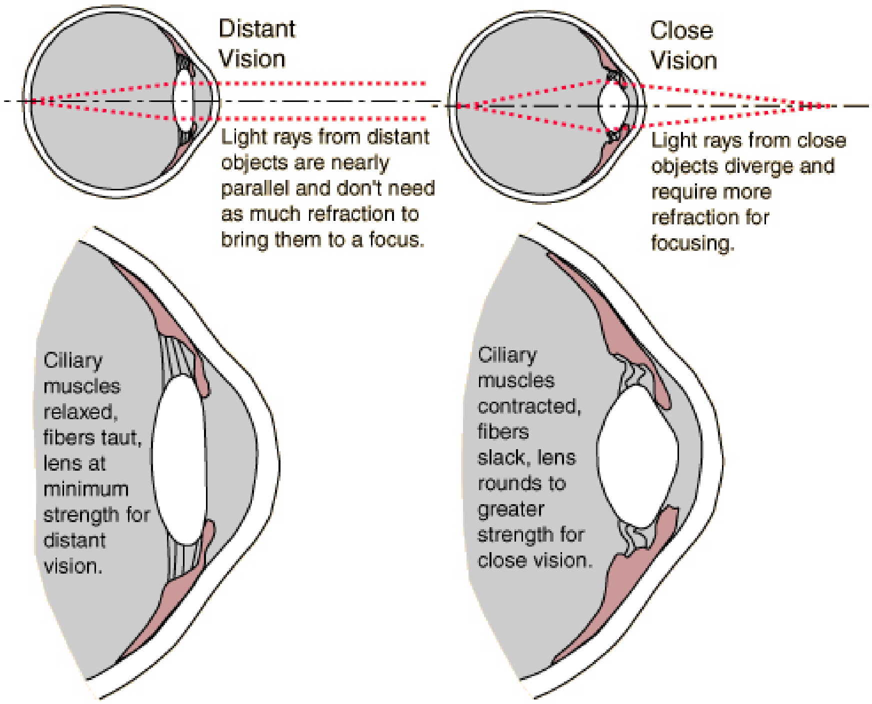


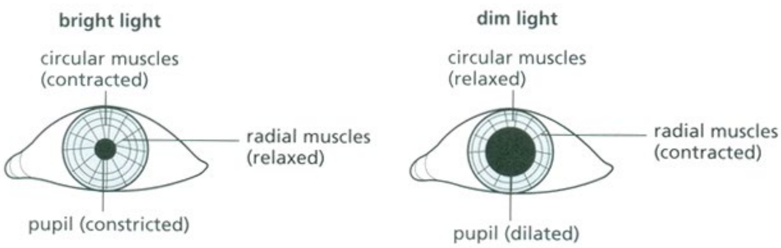
Image Source[28]

Minimum Focal distance

The nearest the eye can focus comfortably depends on its maximum accommodation. This distance, the shortest distance of distinct vision is customary defined as **25 cm**, which corresponds to a standard 40-year-old eye[29].

Aperture[30]

The eye has a variable aperture, the iris, in front of the lens. The iris controls the amount of light falling on the retina by involuntary muscular contractions which change the diameter of the pupil. These contractions help the eye adapt to different light levels. The diameter of the pupil varies from ~2 mm in bright light to 8 mm in darkness (maximal physical aperture), for many purposes it may be taken as **5 mm**.



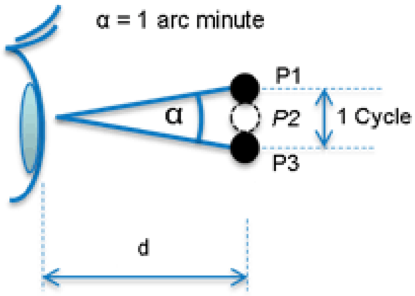
28 http://www.ohiolionseyeresearch.com/eye-center/glossary/accommodation/
29 The eye loses its ability to accommodate, as it ages. This phenomenon is called "presbyopia" and is the reason for corrective lenses for reading distances for middle-aged people.
30 The element that limits the amount of light entering a system is known as an aperture.

Projection Centre & Distance to Projection Plane

The projection center of the eye (approximately, the centre of the human lens) lie **2 mm** behind the cornea and **22 mm** from the photosensitive image surface (the retina).

Spatial Resolution

On the fovea (where the highest visual resolution), two points can be distinguished only if their images are separated by one cone; otherwise, there image is merged. Therefore, the eye can distinguish points that subtend about 1 arc. For an object located at minimum focusing distance, this corresponds to a resolution limit of about **0.1 mm**[31]. Visual acuity falls off rapidly outside the fovea.

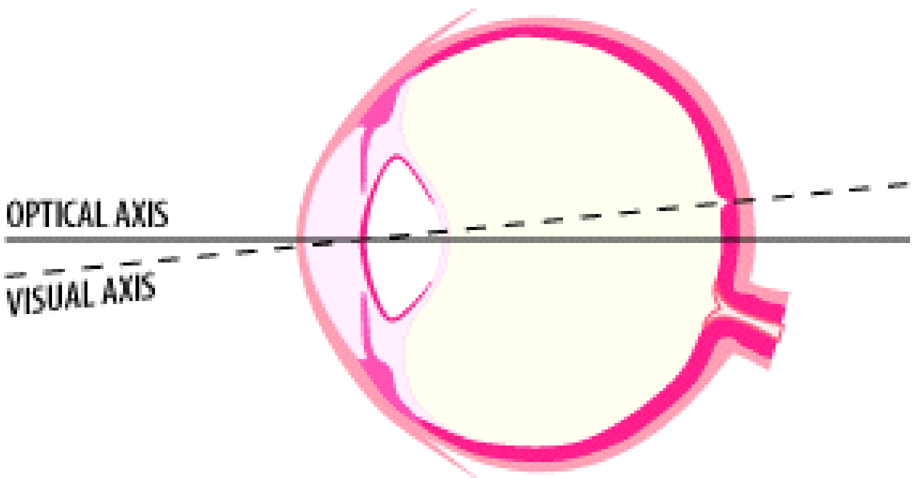


Visual acuity is the spatial resolving capacity of the human eye as a function of viewing distance

Optical Axis vs. Visual Axis

In the case of the human eye, the optical axis is be the most direct line through the centre of cornea to the pupil, the lens, and the retina. This line intersects the retina just below the fovea and does not correspond to the highest visual acuity.

The visual axis is an imaginary line from the centre of the pupil to the fovea. This axis determines the line of sight with the highest radiometric & spatial resolution, but because of the physiology of the lens doesn't intersect the cornea and lens at their exact centres.



Optical vs Visual Axis i[32]

31 The resolution limit estimated in this way is remarkably close to the theoretical resolution limit calculated by diffraction theory for a 4 or 5 mm pupil. Evolution has thus been very efficient at packing cones into the fovea at nearly the optimum density.
32 http://dba.med.sc.edu/price/irf/Adobe_tg/colour/vision.html

ON HUMAN VISION & CENTRAL PROJECTION

Is human vision truly best described by the model of central projection on a flat plane?

Central projection is a representation system that **doesn't accurately describe our empirical reality**. The reasons for this are many.

In the most general sense, we should stress the fact that the actual light-stimuli goes under important and yet uncharted processes in the brain- hence, we can make the distinction between **sight** & **vision**.

Furthermore, sight, in contrast to photography, does not consist of separated, distinct «snapshots». The eye moves about in space and merges the pictures it records into a single, seamless experience. Vision is a product of the **continuous movement and refocusing of the eyes**: each "snapshot" is seamlessly blended in a continuity. «What we really see is our mind's reconstruction of objects based on input provided by the eyes — not the actual light received by our eyes[33]»

But regardless of that, we can note some tangible and specific differences between the premises of central projection and the physiological structure of the eye.

In terms of physiology, we note the **curvature of the projection surface**, i.e. retina, so we deal with a curved surface rather than a euclidean plane. Therefore, one should more accurately study the rules on projections on spherical surfaces, rather than flat ones.

Another factor is the **variation of the density and distribution of cell types** on the retina. This brings about a qualitative trait - an «inequality»- to the projective surface, which is in direct contrast with the simplification of uniform and equal space, which lies at the heart of geometrical abstraction.

Yet another factor is the arrangement of the **«lens» elements of the eye** (cornea and crystalline lens) and the subsequent distortions that are introduced (e.g. radial distortion, unsuitable focal length, the offset of the visual-optical axis, etc.).

** Although the rules of central projection on a flat surface introduced perspective and the convincing illusion of 3d space in the pictorial arts, we have clues to speculate that important thinkers, such as Leonardo Da Vinci, were aware of the inaccuracy. Da Vinci was narrowing a curvilinear perspective (a projection on a curved surface) as a more accurate representation of the visual stimuli/experience. In his writings, he notes that the straight flight of a bird on the sky creates a curved line rather than a straight path.*

Screenshot from film "Man with a movie Camera" (1929, by Dziga Vertov)[34]

33 Cambridge in Colour
34 http://emanuellevy.com/wp-content/uploads/2014/08/The_Man_With_a_Movie_Camera_1_vertov.jpg

BINOCULARITY, DEPTH PERCEPTION & STEREOPSIS

keywords: <monocular/binocular vision, evolution, stereopsis, stereoscopy, overlap, parallax, depth perception, base>

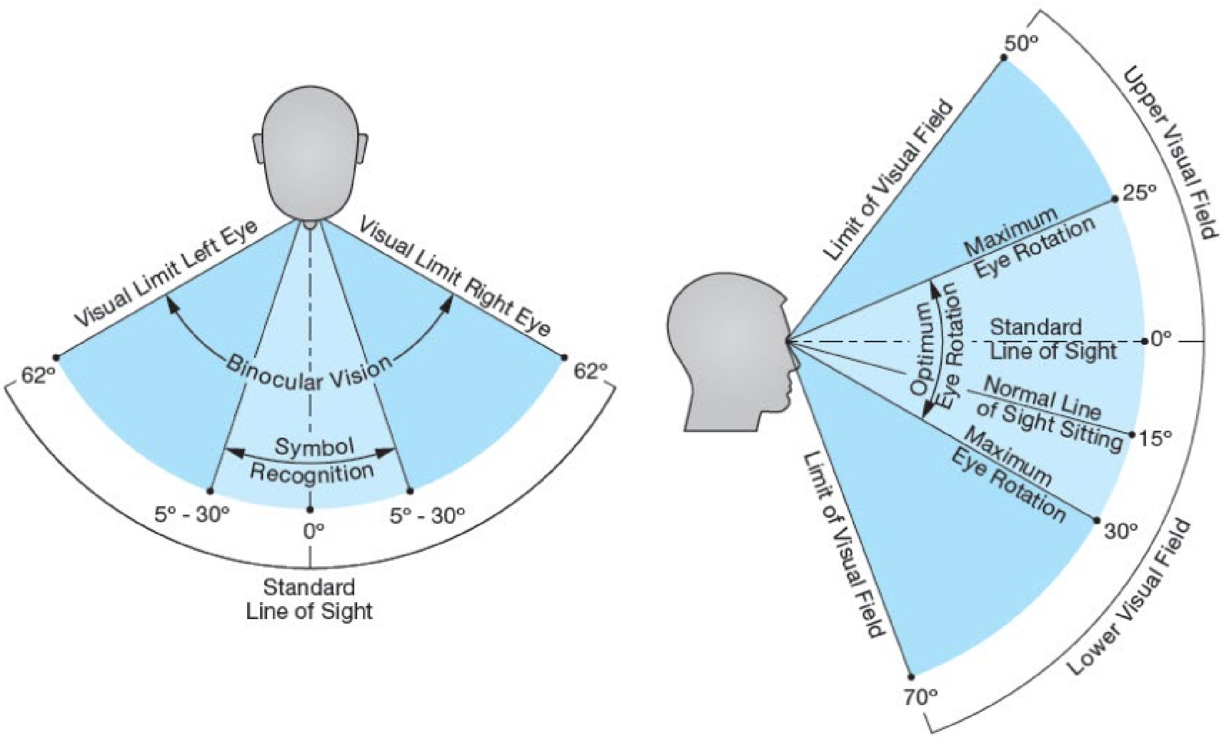
In the previous chapter, we examined the eye as an optical instrument & visual sensor and stated the fundamentals of its mechanism. In the following chapter, we will move on to the basics of binocular vision, which grants us the ability of stereopsis. Stereopsis allows us successful and accurate depth perception, which is one of the fundamental traits of human vision, alongside motion perception, spatial form, colour vision. Not only is stereopsis fundamental to photogrammetry, it is a vital skill to our daily survival and evolutionary success!

Binocularity

Binocular vision has an very high adaptive significance and is a highly complex and sophisticated mechanism in mammals, especially in primates and man in particular[35]. High **orbital convergence** and a **wide visual-field** are key to humans, inherited from our primate ancestry. Evolutionary, large binocular visual fields offer enhanced light capturing ability, contrast discrimination[36] and **expanded stereoscopic depth detection**.

Field of Vision

The frontal position of the eyes, as opposed to lateral, leads to smaller field of vision on the one hand, but offers increased depth perception on the other. Eye configuration is a basic distinction between herbivores and predators: herbivore animals have lower field of vision overlap, therefore higher dependability on motion parallax, since with less retinal disparity cues comes lower depth perception.



Human Binocular Field of View and Overlap

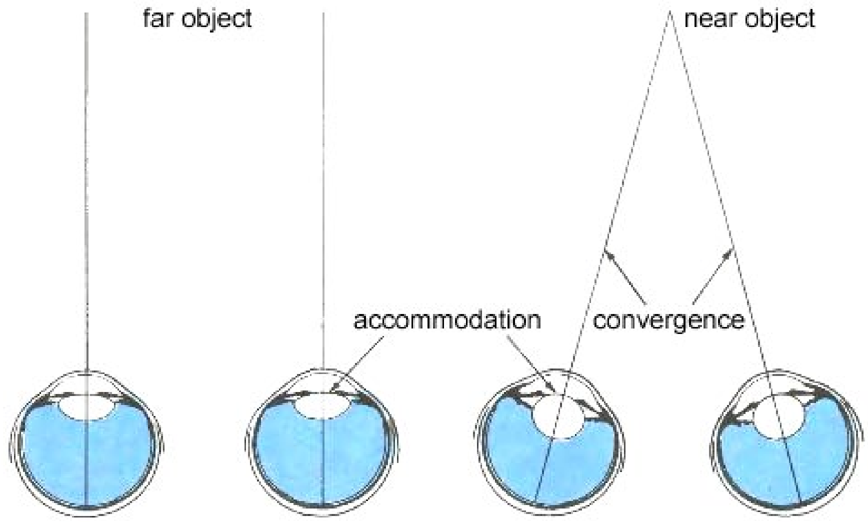
35 On the evolutionary path of binocular vision, see: «J.D. Pettigrew, The evolution of Binocular Vision, 1986» and «C.P. Heesy, Seeing in Stereo: The Ecology and Evolution of Primate Binocular Vision and Stereopsis, 2009».
36 The ability to detect luminance differences in adjacent objects or multiple parts of the same object, especially subtle differences. This helps the brain remove unwanted noise and keep meaningfull variations in textures.

Distance of Human Eyes

The horizontal distance of the human eyes is approx. **64 mm.** If each eye would corresponds to a photo camera, this distance in photogrammetric terms this would be called “base”, denoting the distance between two photo-capturing locations.

Eyes Vergence

The optical axis of the eyes can be regarded as parallel to each other, passing through each “projection centre” and perpendicular to a tangent of the cortex. This is the normal case for focusing on far away objects. When focusing to nearer objects, the optical axis of the eyes converges.



Depth Perception

Depth Perception is the ability to see the environment in three dimensions and to **estimate the spatial distances** of objects from ourself and from each other. The elements of the surrounding that act as cues to assist the brain in this process are divided in three categories: **monocular**, **oculomotor**[37] and **binocular**.

Although monocular cues offer a basic estimation, mainly based on relative relationships, it is through binocularity that successful and accurate depth perception takes place.

Depth Cues

The **information contained in a 2D image** that makes us perceive depth is called a cue. According to cue theory, humans estimate depth by relating the observed cues with accumulated knowledge/familiarity. Therefore, depth perception is regarded as a learned process.

37 Oculomotor cues are based on the ability to sense the position of our eyes and the tension in the eye muscles.

I. Monocular Cues

Based on Location:

- **Occlusion \ Interposition**: the overlapping of farther away object by the closer ones
- Relative height on the image plane\”**Horizon**” : Objects high in the visual field and closer to the (imaginary) horizon line are perceived as being farther away than objects lower in the visual field. Above the horizon line this relationship is reversed, so that objects that are lower and nearer to the horizon line appear farther away than those up higher. (for distant objects)

Based on visual acuity

- **Atmospheric scattering**: Near object have clear and sharp boundaries as opposed to objects in a distance, due to increasing scattering of the light rays by vapour & dust molecules in the atmosphere[38].
- **Scale Variations/Texture gradients**: Generally, as distance increases, the size of elements making up surface texture appear smaller and the distance between the elements also appears to decrease with distance

Based on brightness & colour

- **Shadows**: The shadow cast by shapes offer important information about their relative positioning.
- Variations of **lightning**: the nearer an object is to a light source, the brighter its surface appears to be, so that with groups of objects, darker objects appear farther away than brighter objects
- **Atmospheric perspective**: Objects farther away have a bluish tinge. (for distant objects)

Based on Central Projection

- **Linear perspective**: Parallel lines not parallel to the projection plane appear as convergent in infinite distance.
- **Relative\Retinal size**: Objects of same size diminish in different scale as they move further away from the observer.

Produced by movement

Either a moving target or moving of eyes\head causes motion parallax. Objects nearby appear faster moving than objects in the distance, also, objects in the back are occluded or revealed as a result (deletion or accresion).

II. Oculomotor

- **Accommodation**: As stated, accommodation occurs when curvature of the eye lens changes differentially to form sharp retinal images of near and far objects. It seems that feedback from alterations in ciliary muscle tension may furnish information about object distance.
- **Convergence**: Convergence refers to the eyes’ disposition to rotate inward toward each other in a coordinated manner in order to focus effectively on nearby objects. With objects that are farther away, the eyes must move outward toward one’s temples. For objects further than approximately 6 m no more changes in convergence occur and the eyes are essentially parallel with each other. Feedback from changes in muscular tension required to cause convergence eye movements can provide information about depth or distance.

III. Binocular Cues

Binocular\Retinal disparity:

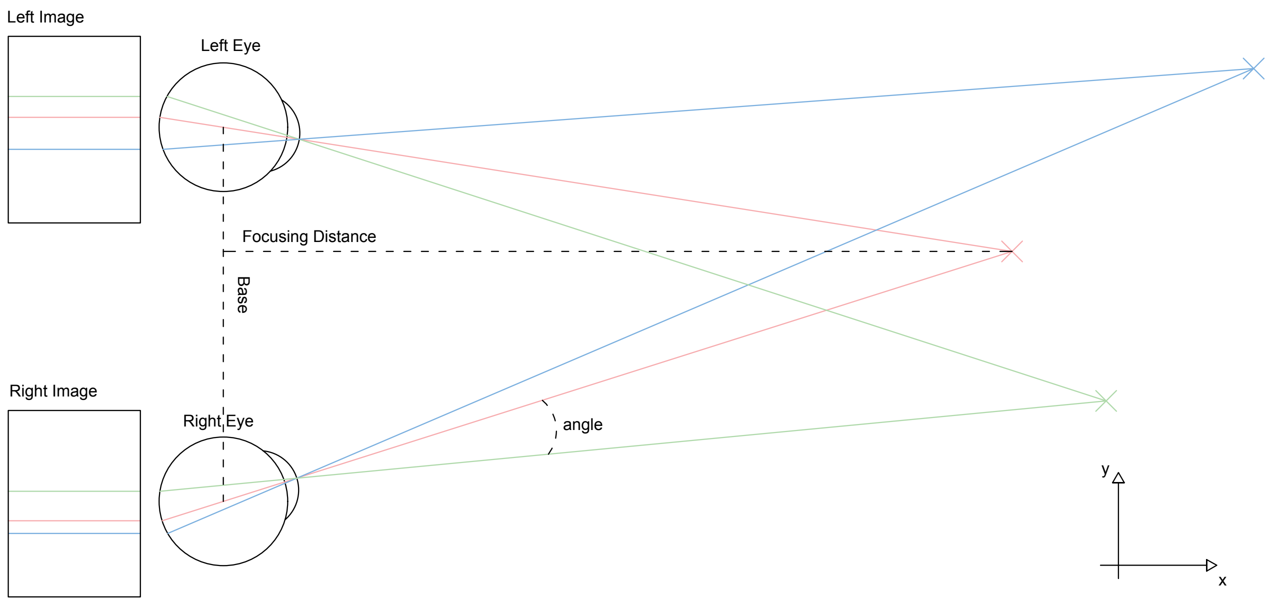
The term “**binocular\retinal disparity**” denotes the small difference between the images projected on the two retinas when looking at an object or scene. Retinal disparity is produced by the horizontal distance of the eyes, therefore The differences of the two images are mainly in the relative horizontal position of objects. This slight difference or disparity in retinal images serves as a binocular cue for the perception of depth. These positional differences are processed in the visual cortex of the brain to yield depth perception.

** Singleness of vision & Binocular rivarly*

Normally two different images are not observed, but rather a single view of the scene, a phenomenon known as singleness of vision. If the images are very different (such as by going cross-eyed, or by presenting different images in a stereoscope) then one image at a time may be seen, a phenomenon known as binocular rivalry.

38 This is why on clear days, very large objects such as mountains or buildings appear closer than when viewed on hazy days.

Parallax
"παράλλαξις", meaning alteration



When a person stares at an object, the two eyes converge so that the object appears at the centre of the retina in both eyes. Other objects around the main object appear shifted in relation to the main object.
Because each eye is in a different horizontal position, each has a slightly different perspective on a scene yivelding different retinal images.
The displacement(difference of the apparent position) of a corresponding point on the images formed from two different viepoints is known as **parallax**.
The intensity of the phenomenon is depended on distance from projection centre. It is usually registered as the difference angle between the two comparing images. Given a known scale of reference, parallax can be used to calculate physical distances.

Stereopsis
Stereopsis is defined[39] as the cortical process that mentally reconstructs a three-dimensional world using binocular visual information, that has been simplified into 2 dimensions by the retinal capture of light from the environment. In other words, **stereopsis is the computation of object solidity and depth based on binocular disparity cues**.

Stereoscopy
Stereoscopy, on the other hand, refers to **techniques for the intended illusion of 3d vision**. It uses the projection of two different views of a scene, precisely captured in such a way, so as to enable the stereopsis mechanism. The stereoscopic technique has been a **great contribution to photogrammetry**.

39 Collins ET. 1921. Changes in the visual organs correlated with the adoption of arboreal life and with the assumption of the erect posture. Trans Ophthal Soc UK 41:10–90.

HISTORICAL EVOLUTION

Photogrammetry’s evolution depended heavily on the evolution of photography. Nonetheless, many more factors come into play. Most notably, geometric optics, projective geometry -both graphical and analytical-, stereoscoping vision, etc. Many of these fields stretch a very long way back into the history of scientific development.

For example, for the theories on the geometrical aspects of light and vision, one can draw the origin back into to classical antiquity, while for their analytical formulation in the more recent past of Enlightenment.

Already from the Renaissance, artists had gained by observation and experimentation a clear understanding of the theoretical rules of perspective depiction, i.e. the way that latent 3d information exists in a 2dimentional image.

Apart from these, it is interesting to note the fact that the rules for stereoscoping viewing had been developed even before the availability of effective photographic devices: for example, the German astronomer Johannes Kepler had already given a precise definition of stereoscopy since 1600.

... of Theories on Light & Vision

יְהִי אוֹר

“Let there be light.”
Book of Genesis 1:3

Primitive, Animistic Thought

Human vision depends on light, that much is plain to notice since dawn of consciousness. In a deeper level, light, sight and truth has been interconnected in our consciousness since time primordial.

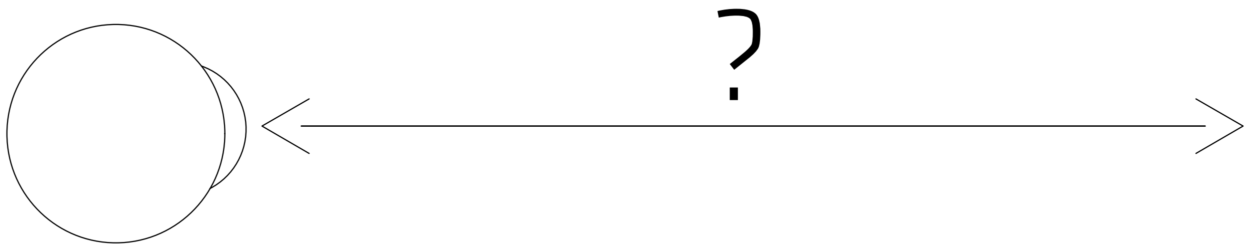
In Western Thought, the first analytical preoccupation with human vision stems from ancient Greek philosophy.[40]

Classical Greek Philosophy

On the shadow of volcano Edna, in mediterranean Sicily, the greek pre-socratic philosopher **Empedocles** [c. 490 – c. 430 BC], a founder of philosophy, physician and poet, described the human eye as a beacon of light, composed by the 4 roots (ριζώματα)[41] of creation -fire[42], air, water and earth- & crafted by Aphrodite. The Eye in his worldview is a godly gift, streaming light illuminating objects, making them thus visible. The shortcomings of his theory were obvious in many scenarios. To account for loss of sight in absence of light, such as in night time and in caverns, he postulated some form of interaction between the theoretical light-rays of the eye and another type of rays that are emanating from light sources, such as the sun.[43] Although partially based on real world observations, Empedocles theories on sight were largely philosophical in their origin, produced by the theoretical tools with which he attempted to explain the rest of reality and therefore in accordance with the larger body of his work.

Foundational philosophical figure, **Plato** (~428–348 BC) adopted this approach too, as did others. On the other hand, **Aristotle** (384 – 322 BC) advocated for a theory of intromission by which the eye received rays rather than directed them outward. He postulated exactly the opposite “όρωμεν εισδεχόμενοι τι, ουκ εκπέμπτοντες”.

Thus the two opposing theories came to be names “**extramission**”[44] and “**intromission**” theory, respectively.



the eye beam as a commonly accepted concept but with different direction

Following Empedocles’ footsteps, the great geometer **Euclid** (c. 325 BC–265 BC) adopted an «**eye beam**[45]» approach to vision. Being foremost a mathematician, Euclid’s thought on vision was guided by

40 Kourniati A.M., (1997) “Οπτικά” του Ευκλείδη και Προοπτικές απεικονίσεις”, Διδακτορική Διατριβή ΕΜΠ. In her work, Kourniati makes a distinction between physical philosophical and mathematical approach to human vision by the ancient greeks. The research on sight is related to medical, astronomical, creational and philosophical interests.

41 Katerina Ierodiakonou, Empedocles on Colour and Colour Vision

42 Theophrastus,Aristotle’s disciple, is attributed to saying that the eye had the «fire within».

43 Empedocles is also credited with other prescient ideas, such as that light travels with a finite velocity.

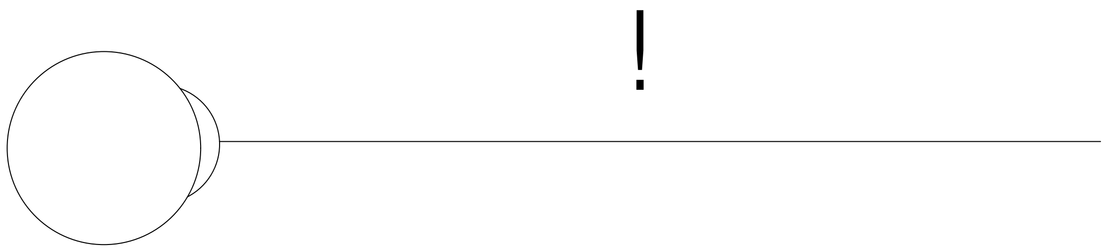
44 It is interesting to note that in a way the extromission theory finds revival and application in image rendering technology at the stage of ray tracing.

45 The eye beam is a archetypical image with strong influence on artistic and mythical thought: we note the enlarged eyes of monumental personalities in busts/statues, references to the eye beam in literature/poems and from the world of myth the monstrous creatures with petrifying gaze such as the basilisk and the Gorgon. Popular superhero culture still derives from this image.

shear logic and deductive reasoning, much in the same spirit as his other monumental work on Geometry, Elements. His studies lead to the creation of the first manuscript that deals in great depth with the geometry of sight, Optics («Όπτικά») and lay a practical foundation stone for future thought many centuries after, reaching up to European Renaissance, affecting creators such as Brunelleschi, Alberti, and Dürer. His contribution is simple and powerful[46]:

"Geometry of straight lines and triangle could solve problems dealing with light and vision."

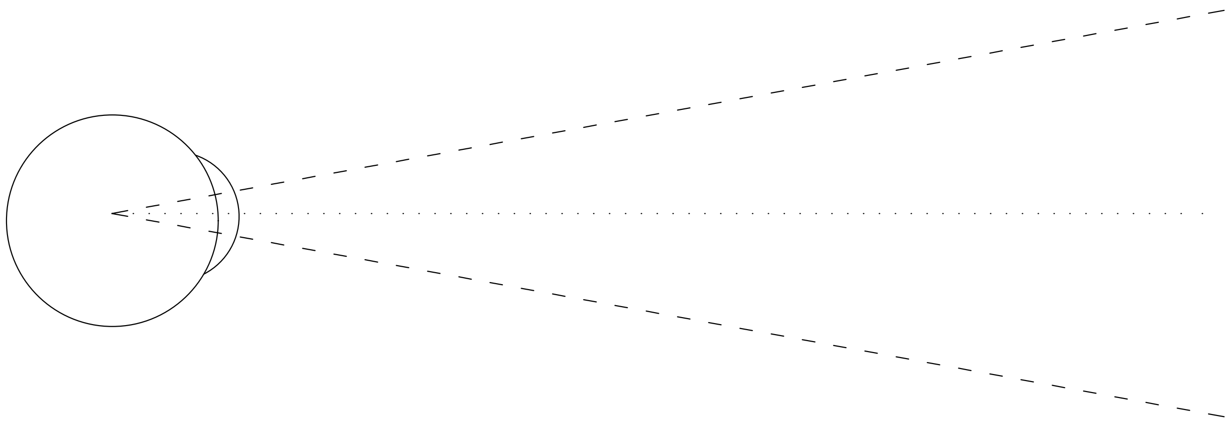
His contribution is valuable despite the adopted false assumption of extramission, exactly because the direction of the supposed light-rays(outward or inward) were non-consequential to his geometrical model. In other words, the geometry of classical optics is equivalent no matter which direction light is considered to be moving in, since light is modelled by its path, not as a moving object.



In Euclid's geometrical interpretation, the direction of the eye beam is unimportant

It is also his purely geometrical approach that allowed him to progress his studies into vision without being hindered by the lack of a theoretical background for the physiological or psychological aspects of sight -it is true that he gives no physical explanation for the nature of his assumed straight lines or rays.

In his work, Euclid begins with 7 postulates and moves on to construct 58 propositions. The whole body of Euclid's describes front **direct vision**. The influence of the observed **correlation between scale and distance** in the visual experience is central in his postulates. He assumes that straight lines connecting the eye to the visible object point and introduces the **visual cone** as the resulting space of vision.



the visual cone

Image Scale- Distance Correlation

Heron of Alexandria (c.10 - 70 AD) moved on to study reflected vision and wrote the first laws of reflection. He demonstrated the equality of the angles of incidence and reflection by means of the shortest path.

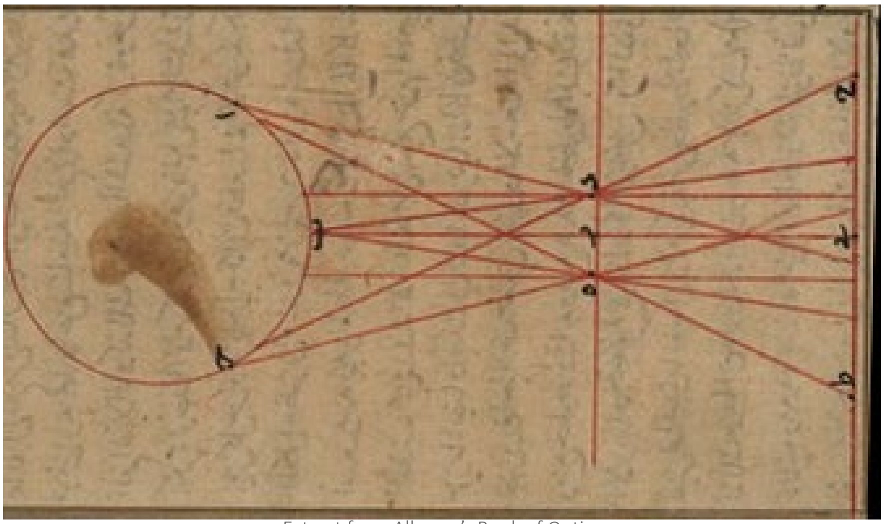
Ptolemy (c. 90 - c. 168 AD) made the step further to include refraction. He wrote about the refraction of

46 Euclid's work found application in areas such as navigation based on stars & sun, exploration and seafaring.

light and developed a theory of vision that objects are seen by rays of light emanating from the eyes. Ptolemy's "Optics" is another greatly influential body of work from Greek antiquity.

the era of Arabic Thought

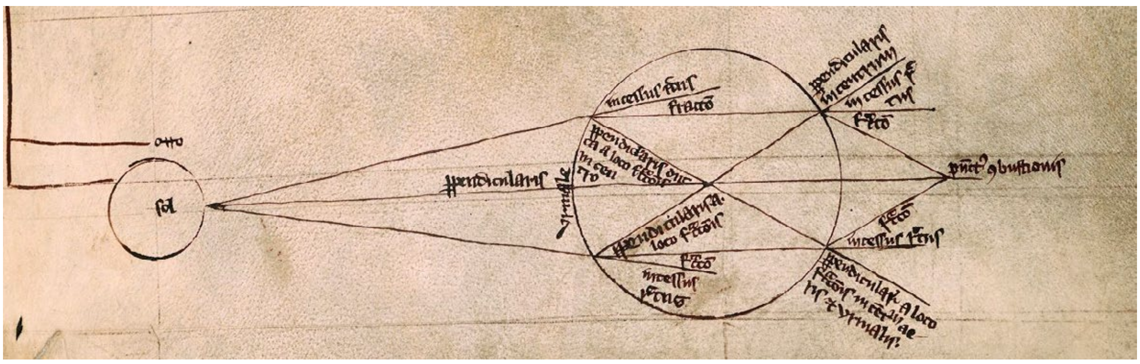
In Arabic thought and in the Muslim doctrine, light has a great religious value. The Muslim scholar, **Ibn_ al-Haytham**, also known as **Alhazen** (965– c. 1040 AD) began his research during the 10 years of house arrest by his patron the caliph (1011-1021) which culminated in discoveries about light & vision. In his greatest work, the Book of Optics, he states that light is comprised of rays traveling through space in straight lines towards our eyes[47], thus overturning 1000 years of accepted notions of extramission. Starting with the reflection on mirrors, which is a pure specular reflection with angular symmetry, he generalised his observations to general reflection and refraction laws. His 7 volume work became a foundation for modern science of optics. Alhazen's theory asserted that «from each point of every coloured body, illuminated by any light, issue light and colour along every straight line that can be drawn from that point»



Extract from Alhazen's Book of Optics

Christian Medieval Thought

In the 12-13th century Alhazen's Book was translated from Arabic to Latin (the book itself was printed in multiple copies in 1572). This re-ushered a stream of Christian thought on light & vision. **Roger Bacon**, a Franciscan frier, studied Alhazen writings and focused on recent glass technology and light, especially curved lenses and the optical distortions they caused. He even experimented in spectacles for correcting problems in human vision. But his main experiments focused on the aspects of light's behaviour. One of his obsessions was the «rainbow effect», given the symbolic value of rainbow based on the bible as a promise after the cataclysm. His rational explanations were counteracting the religious mystery governing the effect which in his strictly theological society led to his confinement.

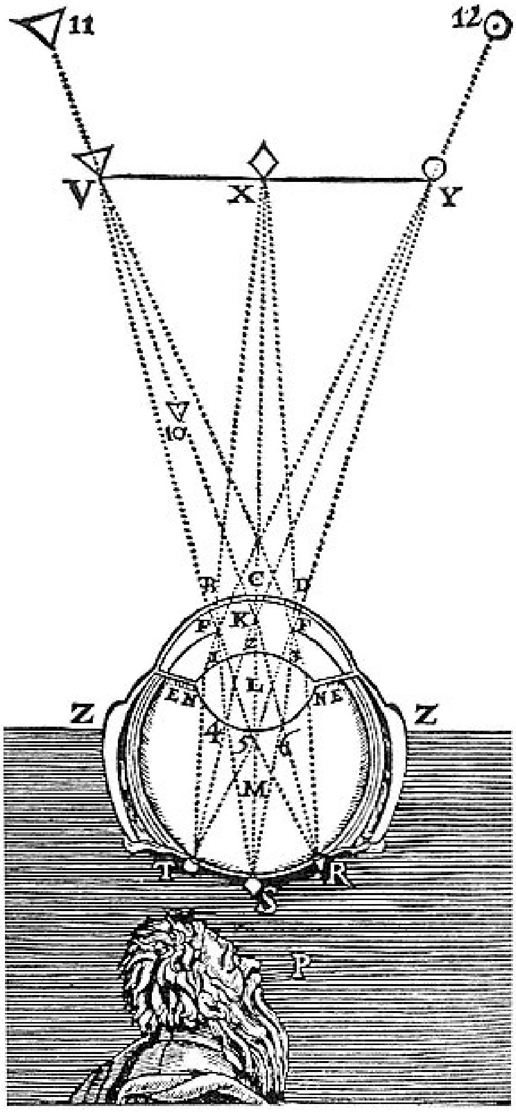


Optical diagram showing light being refracted by a spherical glass container full of water from Roger Bacon's "De multiplicatone specierum"

47 al-Haythan (Alhazen) noted in his Book of Optics that the eye was injured by strong light.

The Era of Enlightenment

Rene Descartes (1596-1650)**,** as part of a mechanical approach to reality adopted the concept of the eye as an optical instrument, thereby exacting anatomical experiments on animal eyes. He discovered the fact that the eye has a glass lens and that it could produce an inverted image on the retina. Moreover, the shape of the eye could change to adjust to focusing distance. Descartes also had a theory on light as particles and colours are constituents of white light.



The formation of the retinal image, as illustrated in René Descartes's La Dioptrique (1637).

Opposing Descartes**, Isaac Newton** (1642-1726) in his study of light and vision in 1664, focused on other ways of creation of visual stimuli. He used prisms on thin sunrays and succeeded in the analysis of white light of the sun. He was the first to use the word spectrum in his crucial experiment to prove that white is composite of primitive colours.

. . . of projective geometry

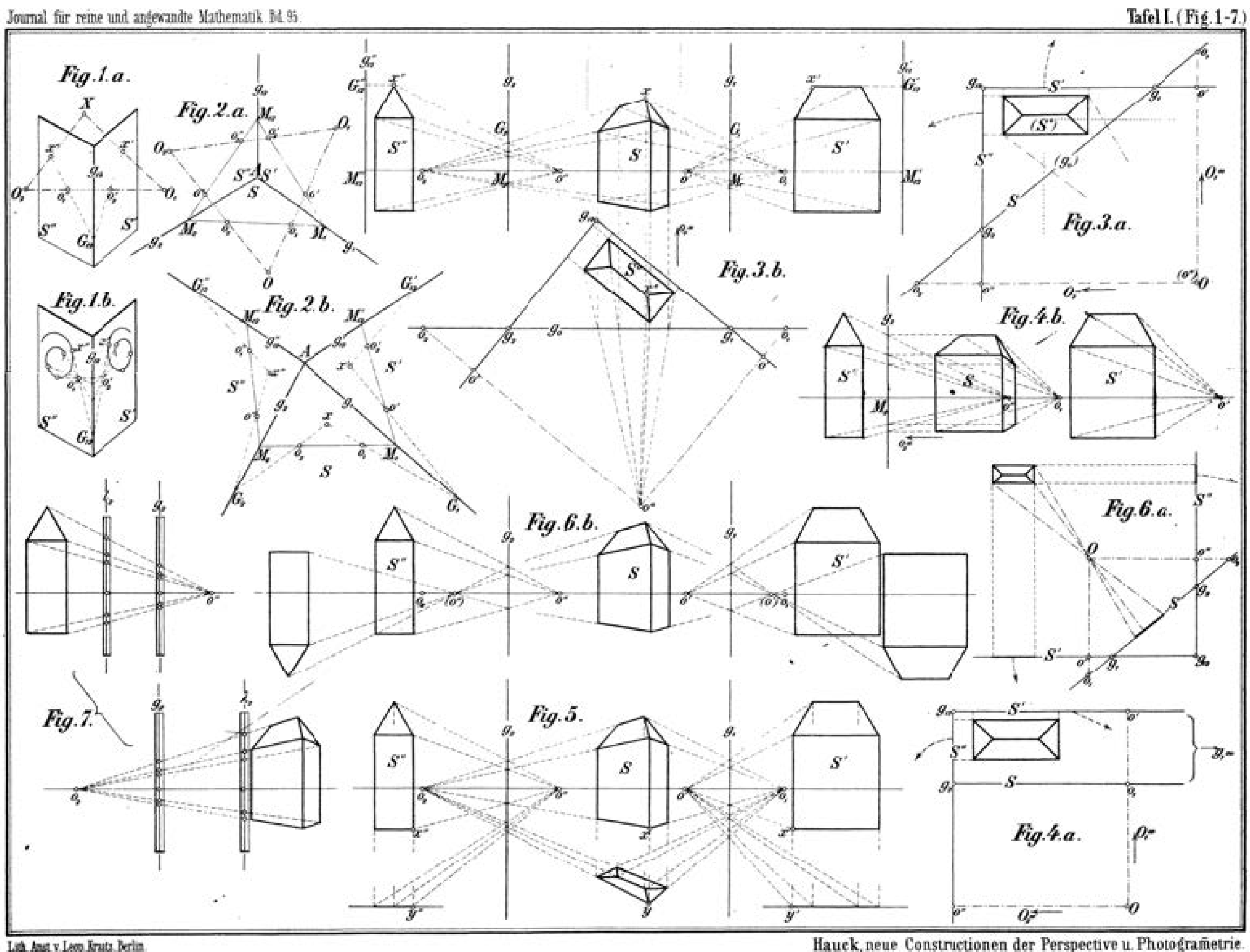
Modern Era Geometry

Projective geometry had a tradition of more than 200 years, before the emergence of photogrammetry. The first systematic treatment of the mathematical laws of perspective drawings was undertaken by the French architect and engineer **Girard Desargues** (1591–1661) and later by his student **Blaise Pascal** (1623–1662). They laid the foundations of the discipline that is called projective geometry.

Important contributions were made by French **Gaspard Monge** (1746–1818). In 1799, Monge wrote a book on constructive or descriptive geometry. This discipline deals with the problem of making exact two-dimensional construction sketches of three-dimensional objects.

Johan Heinrich Lambert (1728-1777) wrote a treaty called the “Free Perspective”/ “Perspectiva Liber” in 1759 discussing the concepts of inverse central perspective and space resection of conjugate images. Using central projection he found the point in space where a photo was taken.

* The relationship between projective geometry and photogrammetry was first developed by **R. Sturms** and **Guido Hauck** in Germany in 1883.



Sketches by Guido Hauck

. . . of Photography

- 1604: Angelo Sala noted that crystals of silver (Ag) turn black when exposed to light.
- 1727: Thomas Wedgwood[48] created the first **photogram[49]**, by placing objects directly on paper surfaces coated with light-sensitive silver crystal emulsion and exposing them to a light source[50].
- 1826: Joseph Nicephore Niepce[51] succeeds in creating the first "fixed" photograph - he names this technique **heliography**.
- 1830: Louis Jacques Mande Daguerre succeeds in creating the first positive photography by coating a silver halide emulsion on a glass plate. This method was difficult to use, needed very large time spans of exposure (~30') and could not produce multiple copies of the negative. He called his method **daguerreotypy**.
- 1834: William Fox Talbot succeeded in creating multiple positive photographs from a single negative.
- 1839: Public disclosure of the pioneering experiments of Nicephore Niepce.
- 1842: John Herschel invented the cyanotype (and many other coating), the photographic fixer for silver halide emulsions, was the first to apply the terms negative and positive, as well as the term "**photography**".
- 1885: George Eastman used nitrocellulose as a film base and later (1890) replaced the photographic dry plate for **roll film**.

48 Called by some historians, the "first photographer".
49 A photogram is a photographic image made without a camera by placing objects directly onto the surface of a light-sensitive material such as photographic paper and then exposing it to light. The usual result is a negative shadow image that shows variations in tone that depends upon the transparency of the objects used. Areas of the paper that have received no light appear white; those exposed through transparent or semi-transparent objects appear grey.
50 Wedgwood was unable to "fix" his pictures to make them immune to the further effects of light. Unless kept in complete darkness, they would slowly but surely darken all over, eventually destroying the image.
51 Niepce was led by his interest in the new art of lithography, for which he lacked the necessary skill and artistic ability, and by his acquaintance with the camera obscura, which at the late 18th and early 19th century was already a popular drawing aid.

PICTORIAL ARTS & PERSPECTIVE

"It was one of the major achievements of the Renaissance period of painting to understand the laws of perspective drawing"

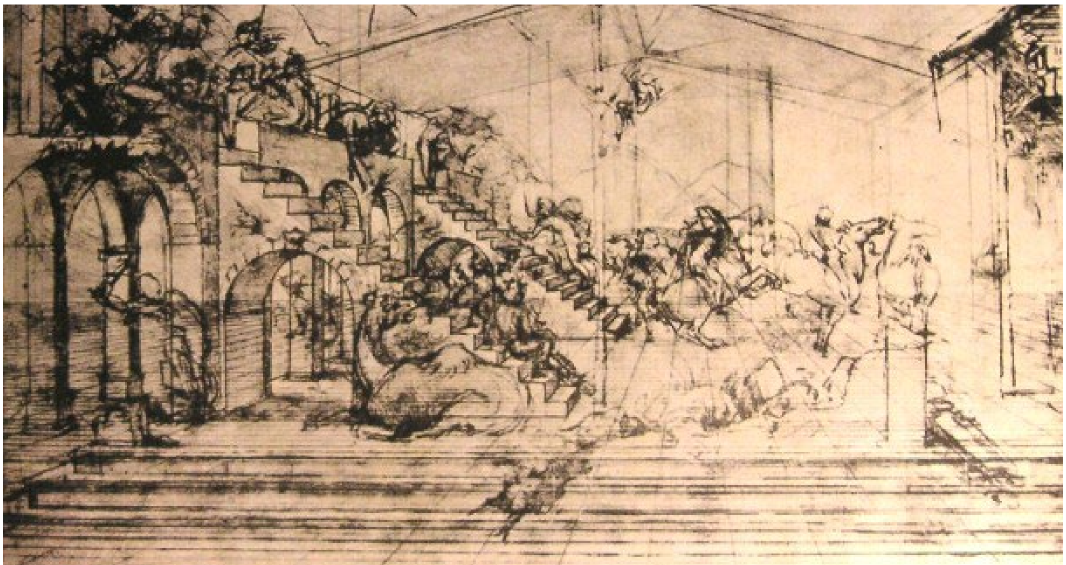
William Hogarth "Satire on False Perspective" (1754)

The rise of perspective in pictorial representative arts began in the **Renaissance** years: It started off shyly with attempts to create a sensation of depth in works and moved on with the full and clear layout of the rules. The appearance of perspective in the pictorial works shows a stable and slow **progressive, empirical understanding** of the intricacies of perspective, rather a full mathematical elegant and unifying solution.

Perspective as a geometrical representation system characterises the Renaissance, but its foundations were already developed in classical antiquity, (among others, in Euclid’s “Optica”), whose study had risen to prominence. This return to **ancient greek studies** together with a **shift to empirical reality** supported the development of central projection.

Noted as the first of his era, Brunelleschi performed demonstrations, exhibiting a mastery over central projection, but no written records remain. Shortly after, **Leon Battista Alberti** wrote down laws for perspective depiction in 1436’s «della Pittura». After him, **Piero della Francesca** in his “De Prospectiva Pingendi” gave a full understanding of the principles of linear perspective.
One of the most important proponents of perspective in painting was **Raffaello Sanzio**.

Leonardo da Vinci (1452-1519)[52], the famed polymath, also explored the disciplines of **optics** and **geometry**. In 1492 he demonstrated the principles of optical perspectivity:
«The art of perspective is of such a nature as to make what is flat appear in relief and what is in relief flat.»
“Perspective is nothing else than the seeing of an object behind a sheet of glass, smooth and quite transparent, on the surface of which all the things may be marked that are behind this glass. The nearer to the eye these are intersected, the smaller the image of their cause will appear”[53]



Display of perspective mastery by Leonardo Da Vinci: Study for Adoration of the magi, 1481

Notable painter and thinker **Albrecht Durer** (1471-1528) wrote a book in 1525 called “Treatise on Mesuration with the Compass and Ruler in Lines, Planes and Whole Bodies” / “Underweysung der Messung, mit dem Zirkel unn Richtscheyt, in Linien, Ebenen unn gantzen corporen”. Using the laws of perspective, he created an instrument that could be used to create a true perspective drawing of nature and studio scenes as well as for producing stereoscopic drawings. The instrument is represented in the woodcut named “The draughtsman and the lute”.

Much later on, we can note the work of pioneering dutch artist **M.C. Escher** (1898-1972), who in his lifetime gained a mastery over perspective depiction and its potential for illusionary depth perception.

52 Σuch mastery that reach anamorphism, the creation of distorted images which viewed from a specific vantage point or through reflection on curved mirror surface, reveal a totally transformed impression. “Anamorphic eye”, 1485 (first known)
53 Doyle, F. (1964) «The Historical Development of Analytical Photogrammetry», Photogrammetric Engineering, XXX(2): 259-265

ON STEREOSCOPY

"This revelation lead to design of several systems where depth perception can be generated. Such displays were called stereo displays. "

Charles Wheatstone (1802-1875) performed intensive experiments to understand the mechanism of stereoscoping vision. His attained knowledge enabled him to construct in 1838 stereoscopic pairs of drawings and a stereoscope with which they could be successfuly viewed imparting on the viewer a sense of spacial depth. He showed that our impression of solidity is gained by the combination in the mind of two separate pictures of an object taken by both of our eyes from different points of view.

Early model of a stereoscope

The "trend" of 19th century was for scene's from paintings to be reconstructed with live models so that they could be photographed from suitable angles and viewed in 3d with the stereoscope

Modern Stereoscope: the Viewmaster

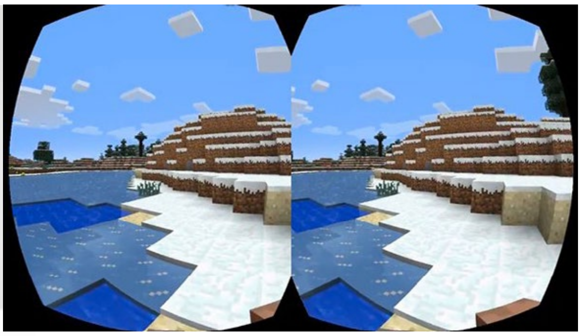
Current day stereoscope:

Smartphone applications (for iOS or android) have been developed for viewing static or dynamic images (video) in stereo, even playing videogames. To this end, attachable viewers have been created to position the mobile in the correct distance in front of eyes and too separate right from left field of view.


Google Cardboard and screenshot from 3d viewing app

The future: Virtual Reality

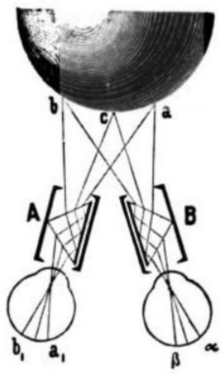
Stereoscoping viewing continues to the digital age, with most notable VI (virtual reality) eyewear, the Oculus Rift, while other available or under development models include Samsung’s Gear VR, Sony’s Playstation VR, etc.



Oculus Rift: Virtual reality head-mounted display and screenshot from videogame “Minecraft”

** Pseudoscope & Reversing Googles*

In 1852 Wheatstone also produced a **pseudoscope**, an arrangement of lenses and pictures in such a way that the viewing field of each eye were exchanged.



Charles Wheatstone’s prismatic pseudoscope