Chapter 2
Data Acquisition for the Geometric Documentation of Cultural Heritage

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Abstract This chapter is divided into five sections. In the first introductory section, the geometric documentation of cultural heritage is defined, while its necessity is also stressed. In addition, the various products which could be included in a geometric documentation are also presented. Moreover, the standards and specifications accepted nowadays are mentioned. In the second section, the passive data acquisition methods are presented. They include those sensors and methodologies which collect data based on the radiation emitted from the objects and have an external—usually natural—source, e.g. the sun. In the third section, the active methods are presented. They include sensors and devices that emit their own radiation and record the part radiating back from the objects of interest. In the fourth section, the contemporary processing methods of the acquired data are presented. They include processing of all kinds of raw data, irrespective of their origin or method of acquisition. Finally, in the last section, three examples are presented in order to enlighten the readers with the various methodologies of acquisition and processing of the data for three representative cultural heritage objects of varying size and properties.

Keywords Geometric documentation • Digital image • Terrestrial laser scanners

2.1 Geometric Documentation

2.1.1 Necessity

Monuments, including immovable structures of any kind and movable artefacts, are undeniable documents of world history. Their thorough study is an obligation of our era to mankind's past and future. Respect towards cultural heritage already had its roots in the era of the Renaissance. During the nineteenth century, archaeological excavations became common practice, maturing further in the twentieth century.

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Over the recent decades, international bodies and agencies have passed resolutions concerning the obligation to protect, conserve and restore monuments. The Athens Convention (1931), the Hague Agreement (1954), the Venice Charter (1964) and the Granada Agreement (1985) are some of the resolutions in which the need for the full documentation of the monuments is also stressed, as part of their protection, study and conservation. Nowadays, all countries in the civilized world are focussing their scientific and technological efforts towards protecting and conserving the monuments within or even outside their borders to assist other countries. These general tasks include geometric recording, risk assessment, monitoring, restoring, reconstructing and managing cultural heritage.

UNESCO (1946) and the Council of Europe have formed specialized organizations for this goal. The International Council for Monuments and Sites (ICOMOS) is the most important. The International Committee for Architectural Photogrammetry (CIPA), the International Society for Photogrammetry and Remote Sensing (ISPRS), the International Council for Museums (ICOM), the International Centre for the Conservation and Restoration of Monuments (ICCROM) and the International Union of Architects (UIA) are all involved in this task. However, all countries of the civilized world are putting their scientific and technological efforts towards protecting and conserving the monuments, either within or outside their borders.

In this context, the integrated documentation of monuments includes the acquisition of all possible data concerning the monument that may contribute to its safeguarding in the future. Such data may include historic, archaeological, architectural information, as well as administrative data and past drawings, sketches, photos, etc. Moreover, these data also include metric information that define the size, form and location of the monument in 3D space, documenting the monument geometrically.

2.1.2 Definition

It was in the Venice Charter (1964) that, before any other form of intervention, the absolute necessity of geometric documentation of a monument was first stressed upon. The geometric documentation of a monument, which should be considered as an integral part of the greater action, the Integrated Documentation of Cultural Heritage, may be defined as [1]:

- The action of acquiring, processing, presenting and recording the necessary data for the determination of the position and the actual existing form, shape and size of a monument in three-dimensional space at a particular given moment in time.
- The geometric documentation records the present of the monuments as they have been shaped in the course of time and is the necessary background to study their past, as well as preserve them for the future.

The geometric documentation of a monument consists of a series of necessary measurements, from which visual products such as vector drawings, raster images and 3D visualizations may be produced at small or large scales. These products usually have metric properties, especially those being in suitable orthographic projections. Hence, one could expect from the geometric documentation a series of drawings that actually present the orthoprojections of the monument on suitably selected horizontal or vertical planes (Fig. 2.1). Two very important properties of these products are their scale and accuracy. These should be carefully defined at the outset before any action on the monument is begun. Depending on the usage of the final product, the scale may be small (e.g. 1:200 or 1:100) or large (e.g. 1:50, 1:20). Accuracy is directly related to the scale factor and could be defined according to the following simple relationship:

$$\text{Drawing Accuracy} = 0.25\,\text{mm} \times \text{Scale Coefficient}.$$

This is based on the fact that the resolution of the human eye on a printed document is approximately ¼ of a millimetre. In the case of digital products, this limit may become more strict, i.e. 0.1 of a mm.

Another important issue is the level of detail which should be present in the final product. For a justified decision on that matter, the contribution of the expert who is going to be the user is indispensable. A survey product, a line drawing or an image implies generalization to a certain degree, depending on the scale. Hence, the requirements or the limits of this generalization should be set very carefully and always in cooperation with the architect or the relevant conservationist, who already has deep knowledge of the monument [2].

In essence, the geometric documentation products are orthogonal projections of a carefully selected set of points. After all, the main data acquisition methods for

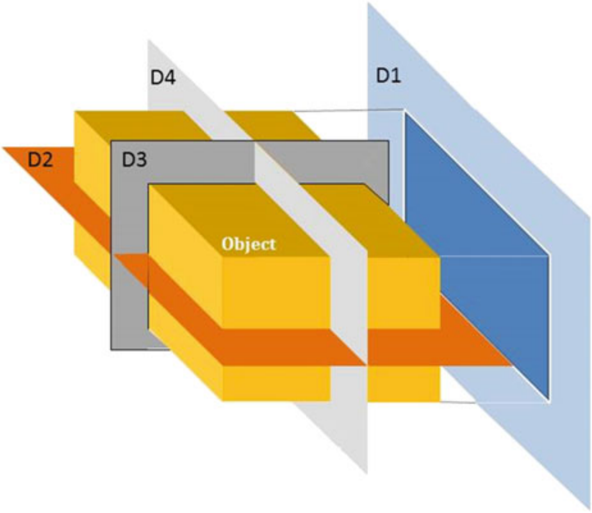

Fig. 2.1 The possible drawings (Di) for the geometric documentation of a monument, horizontal (D2) and vertical (D3, D4) sections and facades (D1)

geometric recording are all point based. The selection of these points requires knowledge, experience and skill. The tools to be used for the determination of these points in space are many and vary in speed, accuracy and efficiency; however, they should all be available to the user.

In any case, the geometric documentation of monuments should serve the needs of conservators and users in general. Hence, it should document those properties of the monument which are necessary to support the right decisions for its conservation. Consequently the monument should be carefully "read" and understood by the documenters as far as its construction, state of conservation and pathologies are concerned. This action calls for an interdisciplinary approach for the geometric documentation of cultural heritage. CIPA,[1] the International Scientific Committee of ICOMOS[2] and ISPRS[3] for heritage documentation, has been striving for many decades to bridge the gap between "users" and "providers" of the documentation products.

2.1.3 Geometric Documentation Products (2D–3D)

These documentation products have traditionally been two-dimensional vector drawings as already mentioned in Sect. 2.2. For many years, users, i.e. architects, archaeologists and conservators were used to working with such geometric documentation products and based their conservation and restoration studies on these.

Technological advances have offered experts the opportunity to produce two-dimensional drawings containing raster images. These images are orthogonal projections of suitably taken digital images and have all the metric properties of conventional drawings. They are referred to as orthophotos or orthoimages. Consequently 2D raster documentation material has come into play, but it needed, and perhaps still needs, some time to be fully accepted by the users, as acceptance has not yet reached 100 %. The main argument is that although the information content is vast, it still needs interpretative action by the experts in order to isolate the necessary information in each case (e.g. geometry, pathology).

3D drawings have also become possible due to the ability of the CAD software to process and present vectors in 3D space. However the latest development is undoubtedly the ability offered nowadays to produce 3D point clouds and from them meshes and surfaces and ultimately 3D textured models. This can be realized quite fast using a multitude of data acquisition techniques. The great advantage is definitely the possibility offered to produce all previously accepted geometric documentation products from these 3D models. Moreover, it is possible to perform

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[1] cipa.icomos.org

[2] www.icomos.org

[3] www.isprs.org

3D measurements directly on these 3D models and set up virtual visits and visualizations, thus serving a multitude of other purposes.

2.1.4 Documentation Methods

For the geometric recording, several measurement methods may be applied, ranging from the conventional, simple, topometric methods for partially or totally uncontrolled surveys to the elaborated contemporary surveying and photogrammetric ones for completely controlled surveys. The simple topometric methods are applied only when the small dimensions and simplicity of the monument may allow it, when an uncontrolled survey is adequate or in cases when a small completion of the fully controlled methods is required.

Surveying and photogrammetric methods are based on direct measurements of lengths and angles, either on the monument or on images thereof. They determine three-dimensional point coordinates in a common reference system and ensure uniform and specified accuracy. Moreover, they provide adaptability, flexibility, speed, security and efficiency. All in all, they present undisputed financial merits, in the sense that they are the only methods that may surely meet any requirements with the least possible total cost and the biggest total profit. To this measurement group belong the terrestrial laser scanners (TLS). They manage to collect a huge number of points in 3D space, usually called point cloud, in a very limited time frame.

It should, however, be stressed that since till date there is no generally acceptable framework for specifying the level of detail and the accuracy requirements for the various kinds of geometric recordings of monuments, every single monument is geometrically documented on the basis of its own accuracy and cost specifications. Therefore it is imperative that all disciplines involved should cooperate closely, exchange ideas and formulate the geometric documentation requirements in common, as well as deeply understand the monument itself and each other's needs.

As it has already been established, the geometric documentation of monuments requires the acquisition of a carefully selected set of points and the determination of their position in space. Hence, all data acquisition methodologies have been developed to serve this exact purpose. Nowadays, there are many available methods for this purpose, and none of them can be considered obsolete. All have a role to play and contribute their share to the final product.

Boehler and Heinz [3] first attempted to illustrate the implementation range of these methods. Today their approach may be adopted to include the newly developed methodologies. In this, the implementation range of each method is characterized in terms both of number of points and object size. More traditional methods include hand and tactile measurements, which are always useful for important details or small objects. Geodetic and tacheometric measurements, i.e. using an electronic total station, although accurate, can only record a limited number of points at a considerable range. Photogrammetry, terrestrial or aerial, is a passive image-based methodology for massive point acquisition from considerable ranges.

Laser scanning or LiDAR, terrestrial or airborne, on the other hand, allows for massive point acquisition using active techniques. For the geometric documentation of monuments, the range of object sizes up to a couple of thousand metres applies, while the number of acquired points should practically have no limit. It should be noted that all methodologies measure angles and distances and indirectly determine the position of the required points in space.

These documentation methods may be grouped in several ways. Firstly, to those involving light recording and those that do not. However, their main distinction is whether they are passive or active. Passive methods record radiation reflected by the objects of interest, while active methods emit their own radiation and measure the returned portion. Image-based measuring techniques are considered passive, and terrestrial laser scanning is active.

2.2 Specifications and Standards

The geometric documentation products are usually used as base material for restoration or conservation studies, where increased accuracy and detail are required. Unfortunately worldwide there are no complete, systematic and accepted specifications recognized as a standard. Moreover, those existing fail to evolve in parallel to and incorporate the rapid technological advances. Consequently, specifications are formed almost ad hoc, especially for each geometric documentation project, which results in a non-systematic approach to this very serious task, and every time the qualities of the documentation products depend on the experience of the experts involved in the compilation of these specifications and not on the particular needs of each case. In addition, the non-existence of specifications causes problems among those who carry out the documentation, those who supervise it and those who are going to finally use it.

Moreover, it would be very useful if the experience gathered from similar projects could be exploited and incorporated into the existing specifications in some form, for the benefit of future projects worldwide. This would only be possible through standardization and specification of the procedures and products. This would also be useful for agencies which are involved with many geometric documentation projects every year [4].

The International Council of Monuments and Sites (ICOMOS) in cooperation with the Getty Conservation Institute (GCI) and CIPA-Heritage Documentation have formed the RecorDIM Initiative, a “Partnership for Heritage Recording, Documentation and Information Management,” aiming to cover the gaps between “users” and “providers” of the information concerning cultural heritage. This would be achieved via the development of strategies and the formation of an action framework. Several task groups were formed, of which TG16 International Heritage Documentation Standards was concerned with studying and analysing international standards and specifications for cultural heritage and compiled a technical report with practical recommendations, technical specifications and standards (RecorDIM TG16, 2007).

English Heritage, now Historic England, on the other hand is using specifications especially developed for the documentation of English monuments [5]. In the USA and within Heritage Documentation Programs of the Department of the Interior and the National Park Service, standards and guidelines were compiled, which to a certain extent cover pertinent needs [6].

In countries with rich cultural heritage, e.g. Greece and Italy, the issue of standards and specifications becomes even more critical. In particular the Hellenic Ministry of Culture (Directorate of Byzantine and Post-Byzantine Monuments Restoration) has compiled specifications, which refer to the requirements of the geometric documentation, but unfortunately enforcing outdated methods [7]. In addition, the Technical Chamber of Greece has attempted to compile technical specifications for restoration and conservation studies, whose main weight however was not on the documentation actions [8].

Consequently, this need should be fulfilled. International organizations like UNESCO and ICOMOS should undertake the initiative, and CIPA is the executive committee to actually compile widely accepted standards and specifications. UNESCO can also offer a great contribution in this area. It can initiate standards and have them implemented by all member countries in the area of cultural heritage. It is then possible to imagine a world database having a uniform format/data structure and guidelines for the documentation of different cultural heritage objects/monuments/sites. With this initiative UNESCO can create a world cultural heritage website “using a common albeit technological language” accessible to the universal public. ICOMOS and CIPA are two professional organizations working together in the area of cultural heritage. ICOMOS has developed and is currently working in the area of e-documentation while CIPA developed the 3-by-3 rules for photogrammetry that are widely used throughout the world today (cipa.icomos.org). These organizations need to be encouraged to continue in this area with common goals and initiatives.

Consequently, surveying and photogrammetric methodology are highly recommended to be the methodologies of choice for cultural heritage documentation. As already described, they are based on direct measurements of lengths and angles on the object or on images thereof, thus resulting to 3D coordinates of the selected points in a common reference system. Their advantages, compared to the conventional methods, can be summarized as follows:

- They achieve the prescribed accuracy for all documentation products.
- They are flexible and adaptable to the particular needs for each object.
- They are characterized by speed, security and efficiency.
- They have the possibility of producing multiple alternative products, such as orthophotos, 3D models and rendered reconstructions.
- They are economical in the sense that they achieve the prescribed result with the least possible effort and cost.

2.3 Passive Data Acquisition Methods

2.3.1 Geodetic Data Acquisition

The contemporary geodetic methodology of data acquisition is mainly employing electronic total stations and is based on the direct measurement of angles and distances in the object space and the indirect determination of the point positions in space. The advantage of this methodology is the possibility for the measurement of specific points with increased accuracy. Obviously, the main disadvantage is the time needed to acquire a large number of points. Technological advances on the other hand are promising that measuring speed will increase in the near future. One such example is the Leica Nova MS50 total station with scanning and imaging capabilities.

Conventional surveying measurements determine a rigid network of well-determined points in 3D space, in order to reference all the subsequent geometric documentation data acquisition methods. Hence, surveying measurements and network establishment should always be performed before any images or point clouds are acquired. Distance measurements with the help of total stations may be performed with or without a reflector. In the case of monument recording, accuracy requirements are increased. In order to meet these accuracy requirements, a very careful setup of the instruments is required and also the manufacturer's specifications for angle and distance measurement should be taken into account. Needless to add that a recent instrument calibration is also required in cases of geometric documentation with increased accuracy requirements.

For the use and measurement performance with a total station, prior knowledge of simple surveying techniques is required. It is absolutely necessary for the user to be familiar with (a) setting up an instrument on a tripod (b) to setting out and measuring a surveying traverse, which is actually defining the desired coordinate system, and (c) handling the total station menu both for the measurements and the downloading of the stored data. To calculate the point coordinates and transform them to the proper system requires basic knowledge of analytical geometry.

2.3.2 Image-Based Data Acquisition

When a large amount of points are required to document the geometry of an object, which is the case for cultural heritage monuments, photogrammetric techniques come to the rescue!! The main task of the various mapping tools, like photogrammetry, is the determination of the shape, size and position of objects in 3D space. Usually these objects are parts of the earth's surface. However, one should not overlook the fact that very often these tools are implemented for "mapping" different kinds of objects, like buildings, monuments—movable or not—and in general objects of different sizes for which the determination of shape, size and position in 3D space is required.

The photogrammetric technique is based on the fact that an image is indirectly recording the directions to all points imaged. Special algorithms are employed in order to "reverse" the process and determine the position of the points imaged on adjacent images in 3D space. According to the International Society for Photogrammetry and Remote Sensing [9], photogrammetry is defined as "The Art, Science and Technique for acquiring reliable information about physical objects and the environment through recording, measuring and interpreting photographic images and patterns of electromagnetic radiation and other phenomena".

It is obvious that this definition by no means confines photogrammetry to a specific kind of image (e.g. aerial image) or to a specific application (e.g. mapping). Photogrammetry in general is a methodology, a tool actually, to perform measurements in 3D space, i.e. measurements of geometric dimensions, such as length, volume, size, form, position and direction, as opposed to pressure, voltage and speed. Very often, however, these measurements are correlated with the determination of other variables, such as the determination of speed through measurement of distance and time. Based on the above, photogrammetry may be characterized as a measuring tool for everything that can be imaged. More specifically what is measured is a 3D copy, a model of the real object. This model may be optical or digital and is conceived by computers or humans. Photogrammetry is in essence an analogue procedure. Under this term it is meant that the object under examination is replaced by a related copy, just like the use of mechanical, hydraulic or electrical analogues in engineering practice.

Photogrammetry is advantageous in cases where the direct measurement of the object is rather impossible, difficult or costly. Naturally an object may belong to more than one of these cases. In addition, one should also mention some other cases which are not concerned with the nature of the object but with the needs which arise during the study of a technical problem. Hence, photogrammetry is also recommended when:

- Large amounts of detail are required from the object's measurements.
- Contours of the object's surface are required.
- It is not certain whether the measurements are going to be needed or not.
- It is not certain beforehand which measurements are going to be necessary and when.

Today photogrammetry is mostly implemented in aerial mapping using airborne or satellite imagery. However, by the end of the nineteenth and the beginning of the twentieth century, the implementation of photogrammetry—with the camera axis mostly horizontal and close to the object—was already developed. The German architect and engineer Albrecht Meydenbauer is considered to be the inventor of architectural photogrammetry as a result of the difficulties he had in documenting high buildings. Since then, the implementation of photogrammetry in cultural heritage documentation has been constantly increasing at the international level.

Most of the international conventions concerned with cultural heritage (e.g. Venice Charter, Granada Convention) specifically mention the absolute necessity of a thorough geometric documentation before any kind of intervention to the monuments. Photogrammetry is an ideal tool for providing a reliable metric base document, which is indispensable for any study. In the interdisciplinary approach, the photogrammetry expert has an important role to play. Needless to say that a complete photogrammetric record of a monument actually constitutes a preservation record, which may be exploited only when needed.

As already mentioned, photogrammetry is a methodology for determining the shape, size, position and also the details of an object in 3D space with the help of images. As a consequence, an important advantage is the fact that at the same time quantitative and qualitative information are recorded in an image. Information about the material, the state, the colour, etc. of the object may be later extracted through suitable interpretation of the image. This record is performed at a given moment in time, which enables the recording of time, as the fourth dimension, thus enabling the monitoring of objects and phenomena variating with time. Additional advantages of the methodology are:

- Most of the processing is performed in the laboratory, thus contributing to lower labour costs and minimizing the work on site.
- Storing and archiving of all information recorded in images is easy and economical.
- Photogrammetry in general is a non-contact method, which is very important for recording and measuring sensitive or hazardous objects.
- Fieldwork is rather independent from weather conditions.

Perhaps the most important step for implementing photogrammetric techniques is the data acquisition. Taking the correct images is essential for extracting the required information from them later. Special care should be taken as to what camera or cameras to use, while the lenses used and the placements (of camera) play an equally important role.

Nowadays, digital cameras are mostly used for photogrammetric applications. However, there are still some implementations of analogue cameras, especially in the field of aerial mapping. Since metric information is to be extracted from the images, the geometric properties of these images and, of course, of the cameras used to acquire them should be controlled and known. Hence, for many decades during the analogue and analytical era of photogrammetry, special cameras were built specifically for metric information extraction with very accurately known geometric properties. These cameras were characterized as metric cameras and presented the following basic properties:

- Stable and known geometry, to increase metric accuracy
- Fiducial marks, to define a reference system for image coordinate measurements
- Low radial distortion, to minimize geometric errors
- Film-flattening devices (mechanical, pneumatic, etc.)
- Fixed focusing distance, to avoid moving lens elements and enhance camera geometry

Metric camera manufacturers provided their clients with a calibration certificate, which describes in detail the camera geometry. Several procedures for calibrating the cameras have been developed as cameras ought to be recalibrated every 2 years or so [10]. Special metric cameras for terrestrial use were also produced by large camera manufacturers, such as Wild, Zeiss, Zeiss Jena, etc. Today digital airborne cameras are the standard for aerial photography. They still have the drawback of the small image size, as technology is still unable to compete with the $230 \times 230\ \mathrm{mm}^2$ negative size of the analogue film cameras. Hence, several techniques are being employed in order to overcome this obstacle, such as implementation of the three-line scanning method (e.g. Leica ADS series) and the composition of a larger image size by stitching together smaller images from the same perspective centre (e.g. Z/I DMC series or Microsoft Vexcel Ultracam series). Today a lot of manufacturers produce digital cameras for aerial images. Aerial imaging is rather outside the scope of this chapter, and for further information the reader is advised to visit the web pages of the manufacturers.

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. With the advancement of computer power and the development of suitable software able to perform camera calibration of high standard, non-metric cameras became more attractive and, nowadays, all digital cameras used for terrestrial applications are non-metric. For cultural heritage documentation, commercial digital cameras are used today. They may be either high-end DSLRs or compact cameras. Each category has its pros and cons. The DSLRs have large sensor sizes and consequently bigger pixel pitch, extremely important for metric imaging. Moreover they have the undeniable advantage of interchangeable lenses, which makes them highly versatile. On the other hand, they are heavier and more expensive. The compact cameras are light and of low cost, but their small sensor size and unstable internal geometry are disadvantages that cannot be overlooked.

2.3.2.1 Digital Cameras and Their Operation

Digital optical cameras have nowadays replaced analogue cameras almost completely. They are the result of the development of the digital sensors, which started in the 1960s. Digital sensors are based on the property of silicon dioxide to generate electric current when exposed to light. Thus two similar technologies have been developed over the years for constructing and operating digital sensors. These are the charge-coupled device (CCD) and the complementary metal–oxide–semiconductor (CMOS). Essentially they differ in the way the intensities at each sensor element are read and converted to digital information.

2.3.2.2 Characteristics

Colour is attributed to each registered sensor element intensity using the Beyer principle by which each sensor element (sel) has a filter in front and registers the intensity of the respective colour band, i.e. red, green or blue. The green "sensitive" sels are double in number compared to the red or the blue ones to exactly simulate the way the human eye perceives colour. Of course there are other systems to attribute colour to the digital image, but they are used by very few manufacturers, e.g. the FOVEON system used by Sigma[4] and the Multi-Shot system employed mainly by Hasselblad.[5]

Another very important, but often overlooked, property of the digital sensors is their size, especially the size of the sensor elements, also known as pixel pitch. As the sensor elements vary in physical size and the number of sensor elements—which will later become pixels in the digital image—it would be useful to pay attention to the following parameters. For a sensor element to register reliably the intensity of light, it should have a size of more than 4 μm, i.e. 0.004 mm. Hence, the combination of the physical sensor size and the resolution, usually given in megapixels (MP), is of utmost importance in order to ensure reliable digital image registration.

Digital sensor sizes can vary from a few mm^2 up to the "full frame" for the commercial compact and DSLR cameras and even bigger for specially developed digital systems.

2.3.3 The Digital Image

The replacement of analogue film with electronic chips has introduced a new reality as far as the internal geometry of the camera is concerned. On one hand the imaging plane

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[4] http://www.foveon.com/article.php?a=67

[5] http://www.hasselblad.com/digital-backs/multi-shot-digital-back

is almost by definition planar, but on the other hand the size and shape of the pixel are introduced as new parameters. On the other hand, digital recording has also introduced some problems and defects as far as radiometry of digital images is concerned, such as dark current, blooming, smear, traps and blemishes to name but a few. All these contribute to the final quality of the digital image and, consequently, to the final accuracy of the measurements and reliability of imagery products.

One of the most important problems caused by digital recording is noise. By that all useless radiation recorded is meant, which is caused by a number of sources, such as the ambient conditions and the electronic chip itself. The ratio of useless radiation recorded to the useful signal is the measure of noise, and it is called the signal-to-noise (SnR) ratio and is measured in dB (Fig. 2.2).

Digital recording has clear advantages over the obsolete analogue film, some of which are the following:

- Lower cost
- Lower noise

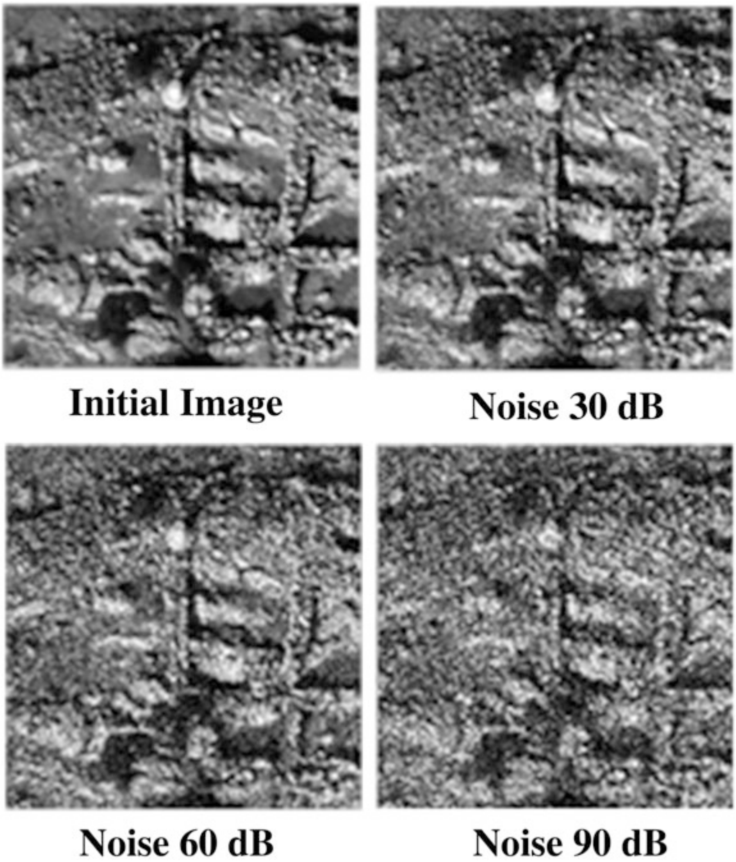


Fig. 2.2 Noise in digital images

- High dynamic range
- Reliability
- Stable geometry
- No processing—developing—time
- Possibility for real-time processing

Today digital cameras are in their phase of maturity, after almost three decades of existence. In this section, some principles of digital image processing will be presented for the benefit of understanding the photogrammetric processing of digital images.

A digital image is defined as the depiction of the object of interest on a planar surface using a finite number of picture elements (pixels) for which their position (i, j) and grey tone (or colour) value $(f(i, j))$ are known. This implies that the image is actually a set of numbers; hence, it may be stored and handled by a computer. On the other hand, it is a discrete imaging function as opposed to the analogue image, which is considered to be a continuous one (Fig. 2.3).

This set of numbers, which forms the image and actually only the colour values, has some interesting statistical properties, which are characteristic of the digital image itself. Let us suppose that there is a digital image of C columns and R rows (Fig. 2.4). The mean value m of the set of colour values is determined as:

$$m = \bar{f}(x, y) = \frac{1}{CR} \sum_{x=0}^{C-1} \sum_{y=0}^{R-1} f(x, y).$$

This mean value is indicative of the brightness of the image. The bigger the value, the brighter the image. The variance var of the set of colour values is determined by:

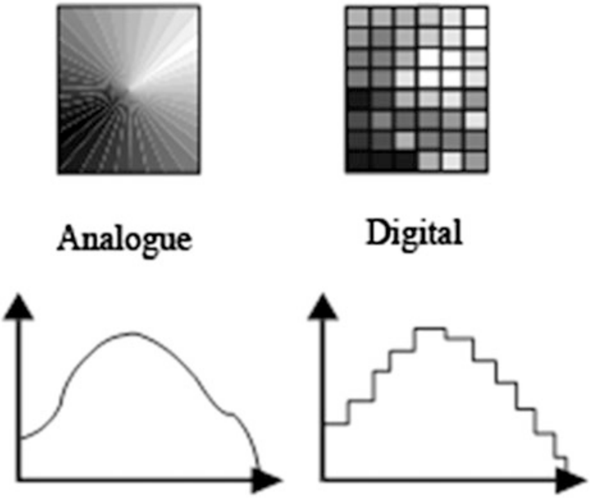


Fig. 2.3 Analogue and digital image

Fig. 2.4 Structure of a digital image

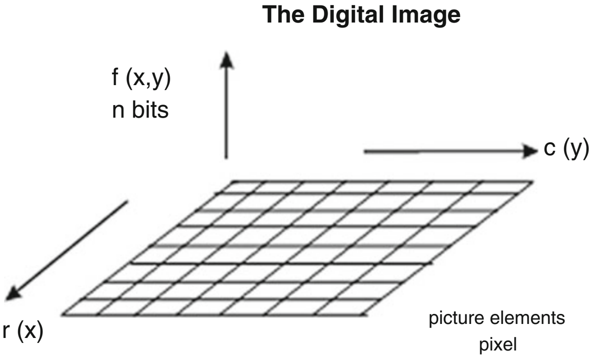
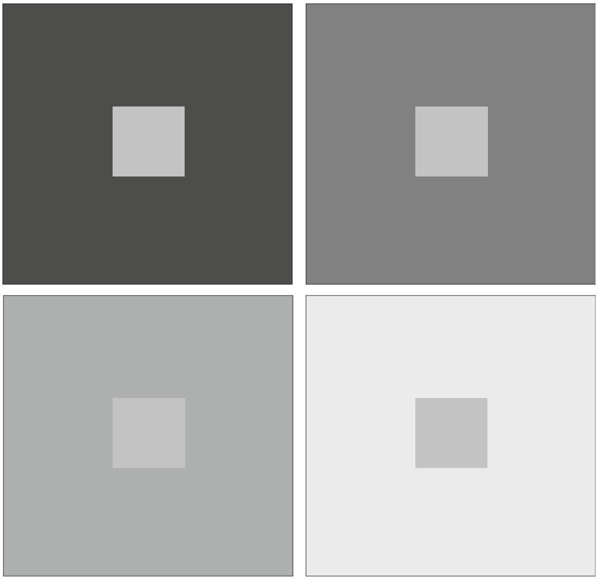


Fig. 2.5 The relativity of the contrast



$$var = \frac{1}{CR}\sum_{x=0}^{C-1}\sum_{y=0}^{R-1}\left(f(x,y)-m\right)^2$$

The variance is expressing the contrast of the image. The bigger the value of var, the more contrast is present in the digital image. It should be noted that contrast is rather a subjective property, as it is dependent on the background and surrounding colours (or grey tones). In Fig. 2.5 this relativity is depicted as the squares in the middle have exactly the same colour value, but they seem different to the observer.

Finally, the histogram of the digital image, i.e. of the grey (or colour) values, is actually the frequency of appearance for each value in the image and is indicative of the quality of the digital image. The wider the value range is, the better the quality of the image, as it stretches over the whole range of the available grey tone (or colour) values.

Spatial resolution of an image is related to the physical size of each pixel and, of course, their number in the digital image. It is obvious that the smaller the size of each pixel, the better the measurement accuracy on the image but the bigger the size of the file. Today the physical size of the pixels is down to a few micrometres (1 μm = 0.001 mm). However, there are limitations, since a pixel of size smaller than 4 μm is unable to reliably record enough photons in order to register the grey tone (or colour) value for that pixel, and interpolation is used to cover this deficiency. Hence, pixel sizes of less than that value in size should be avoided for metric use. Earlier, spatial resolution used to be measured in dots per inch (DPI) as a result of the older digitization process on scanners. Nowadays, we tend to measure spatial resolution by the physical size of the pixel in conjunction with the physical size of the sensor. This last value is not very easily known by the manufacturers, who tend to promote the amount of pixels (MP) for obvious commercial reasons. Alternatively, we tend to use the GSD (ground sampling distance), which is the size of the object imaged in a pixel of a digital image at a given scale. In Fig. 2.6 the

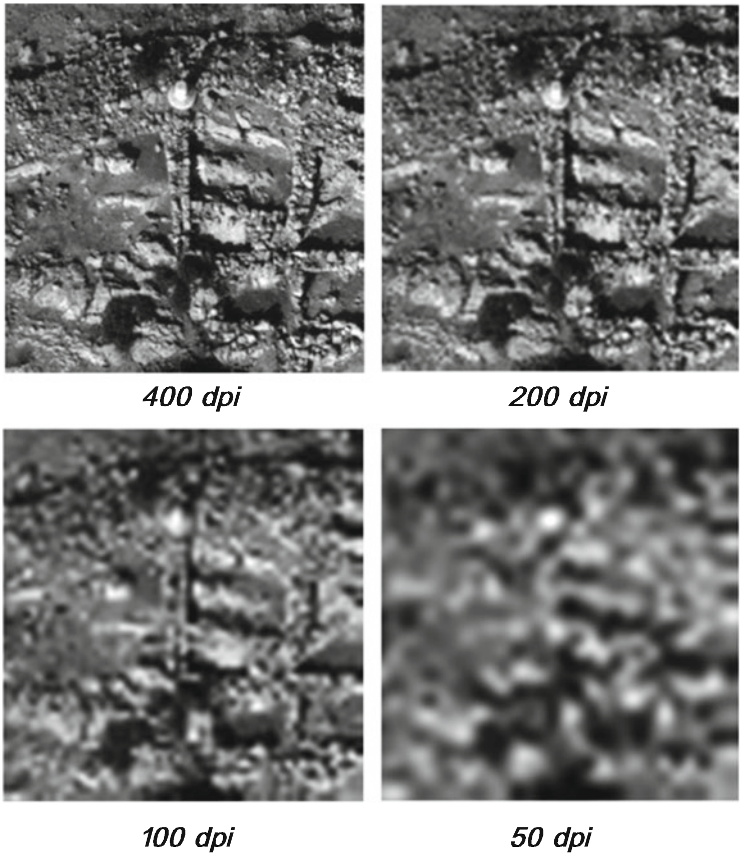


Fig. 2.6 Image spatial resolution

Table 2.1 File size and spatial resolution of an aerial B&W image

Spatial resolution	1000	600	300	100	dpi
Size of image file (23 × 23 cm^2)	80.1	28.8	7.2	0.8	MB
Pixel size	25.4	42.3	84.7	254	μm
GSD for image scale 1:8000	0.20	0.34	0.68	2.00	m

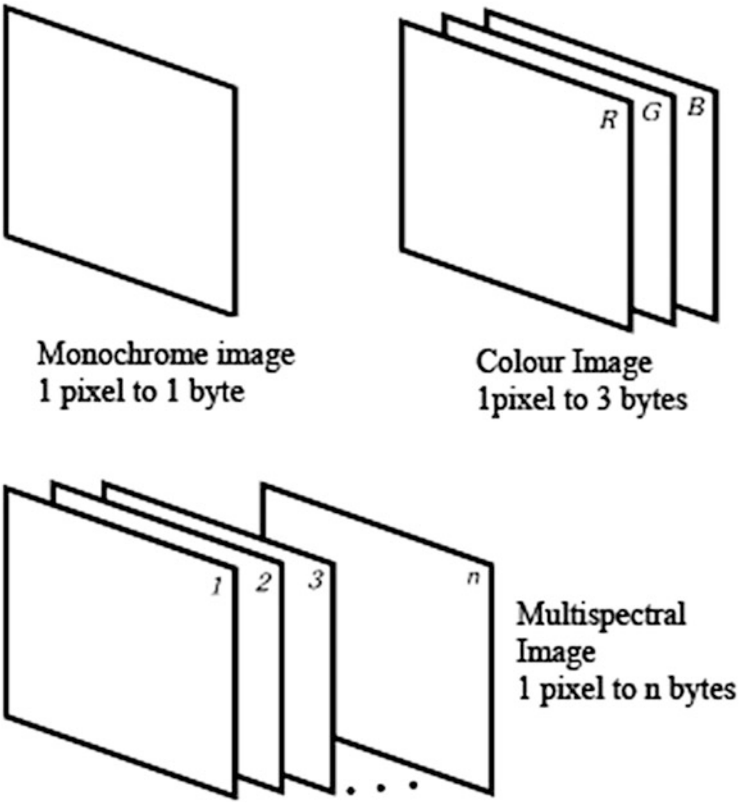


Fig. 2.7 Colour depth of a digital image

same image is shown with different spatial resolutions, and in Table 2.1 the size of an analogue aerial image (negative size of 23 × 23 cm^2) digitized for different spatial resolutions is presented.

Radiometric resolution, on the other hand, is related to the number of grey values (or colours) that are used in the available palette to describe the image. If the image is black and white, only grey values are used. If it is coloured, which is the most common case nowadays, a combination of the basic colours, i.e. red, green and blue (RGB), is required to assign colour to each pixel (Fig. 2.7). It is interesting to note that the multispectral satellite images also use the same principle. The number of available colours has a direct effect on the size of the image file and on the amount of the imaged detail. The more colour values are available, the more details are

Table 2.2 File size and radiometric resolution of an aerial B&W image

Radiometric resolution Number of values	Black	White	Bit	Pixel/byte	MB
2	0	1	1	8	10
4	0	3	2	4	20
16	0	15	4	2	40
256	0	255	8	1	80

depicted in the image, and, consequently, measurements may be performed with more accuracy.

The amount of available colours is also related to how this information is stored. For each pixel one number is assigned. If this number may take only two values (2^1, e.g. 0 and 1 or black and white), then for its storage only one bit (binary digit) is required. If the possible values are four (2^2), two bits are required and so on. Today the most usual way of describing colours is by using 256 (2^8) different grey values or 3×256 values for RGB, i.e. for a colour image.

In Table 2.2, the size of the image files is given for a 1,000 DPI (25.4 μm pixel size) black and white digital image for different radiometric resolutions.

There are many different ways to store a digital image in a file. Over the years many image file formats have been developed, and there is no standard today that clearly supersedes the others. The image information is codified in a certain way and stored in the digital file. Special software is required to de-codify the file and present the image on the screen or process it in any other way. Some file formats compress the image information for the sake of smaller file sizes with negative consequences on the image quality. In addition there are standards introduced by all camera manufacturers to store their images in proprietary RAW format, which is different for each one of them.

In the image file, there is usually a header with information about the image, such as number of columns and rows, pixel pitch and resolution, and then the actual image information follows. The formats mostly used today to store digital images are Tagged Image File Format (TIFF) and Joint Photographers Expert Group (JPEG) or JPEG 2000.

2.3.4 Good Practice for Digital Imaging

The geometric recording of cultural heritage assets implies in essence the projection of a carefully selected set of points on horizontal or vertical planes, thus forming the required 2D drawings, which traditionally form the basis of all intervention studies. The fact that nowadays 3D models have also undertaken a significant role in these actions has not affected this principle, as 3D models are actually a set of millions of points, not carefully selected this time. Terrestrial image-based techniques for recording and documentation are based on the fact that through the camera an infinite number of angles from the camera station to the points of the object imaged are recorded. The photogrammetric procedure is then responsible to extract metric information, i.e. to determine the position in space of the selected or all of these points. This may be achieved using two different but similar pathways: the typical photogrammetric pipeline or the automated approach using the structure-from-motion (SfM) algorithm.

2.3.5 Platforms for Data Acquisition

Positioning the camera for metric photography is most of the times crucial. The images have to be taken from specific positions with certain orientation. These parameters contribute to the correct image scale and GSD, to the required coverage and, most importantly, to the correct orientation of the camera axis. Consequently, it is often necessary to employ special means to position the camera to the desired position. The platforms employed for that purpose may be limited only by imagination.

Tripods, scaffolding and cranes are perhaps some obvious solutions. However, kite systems and balloons, manned or unmanned, have also been employed in the past. Of course, helicopters, airplanes and satellites are also common practice (Fig. 2.8). Kites, tethered balloons, airships, remote controlled airplanes and

Fig. 2.8 Platforms for aerial photography

helicopters and multirotor and fixed-wing systems are unmanned aerial vehicles appropriate for large-scale mapping [11].

All these different platforms present advantages and disadvantages, which are summarized in Table 2.3. This table also includes the more recently used platforms, namely, the unmanned aircraft systems (UAS). These systems, no matter which kind, have experienced an incredible boom for large-scale mapping and in the geospatial domain in general [13].

Over a short period of time, a plethora of UAS platform types and, most importantly, a multitude of cameras and other sensors have been made available and are being implemented with different and often uncontrollable results. Sometimes their combinations also challenge the implementation of conventional aerial photography for certain applications [14]. Legislation is another critical issue when unmanned aerial platforms are involved, as it varies a lot from country to country, if rules apply at all. Gradually, however, most of the countries pass pertinent laws governing the flight and use of these UAS.

UAS can be remotely controlled, semi-autonomous, autonomous or be driven by a combination of these capabilities. The flight trajectory of a UAS depends on flight dynamics and flight management systems and displays larger off-nadir deviations in contrast with the traditional airborne blocks.

Multirotor and fixed-wing aircraft stand out from the others because of their recent upgrade to assisted or fully autonomous systems. Furthermore, the acquisition accuracy is increasing with these systems, and they are becoming less weather dependent. Multirotor UAS are widely used for surveying smaller areas due to the fact that they can fly in lower flying heights but have shorter flying autonomy. They display greater stability in the wind, and therefore the obtained images are suitable for photogrammetric use. Fixed-wing systems stand out for their increased autonomy and the capability of covering wider areas, as a result of the larger flying height and the greater flying speed they can achieve. However, enough space is usually required for their takeoff and landing. A significant difference between these two groups of systems is the capability of multirotor systems to obtain oblique imagery.

Simple compact digital cameras are usually attached on a UAS. However, they can also be equipped with thermal or infrared camera systems, airborne LiDAR systems, SAR or a combination thereof. In order to define the position and the orientation of the acquisition platform, other navigation sensors are used, such as miniature global positioning systems (GNSS) and inertial measurement units (IMU), compasses and barometers.

Relative recent literature includes studies about the usability of UAS in cultural heritage mapping or surface measurement [15–17], using different UAS acquisition platforms [18], combination of terrestrial and aerial UAS data for 3D reconstruction evaluation [19] or assessments on UAS data dense matching [20].

For close-range applications, which mostly concern the documentation of cultural heritage and especially for taking close-range vertical images from a height greater than the human abilities but smaller than the normal and allowed flying heights of aircraft and helicopters, there was always a desperate need for platforms capable of flying at low altitudes [11]. Nowadays, technological advances have

Table 2.3 Rough evaluation of aerial photography platforms [12]

	Cost	Maintenance and running costs	Deployment time	Experience needed	Time of flight	Weather dependency	Acquisition speed	Acquisition accuracy
Kite	3	3	1	1	2	1	2	0
Balloon	2	2	1	3	3	0	0	2
Airships	1	2	1	3	3	1	0	2
RC single and multicopter	1–0	2–0	3	0	0	2	1–2	3
RC plane	1–0	2–1	2–3	0	1–2	1	3	3
UAV multicopter	1–0	2–0	3	2	0	2	1–2	3
UAV fixed wing	0	2–1	1–3	2	1–2	1	3	3

enabled the manufacturing of a variety of autonomous aerial platforms, which are capable of carrying a digital camera and perform aerial imaging from a few meters to a few hundred meters.

The use of UAVs or UAS or RPAS or drones as they are more popularly known is usually and almost associated with surveillance projects and military action. As the request for timely, accurate, high-resolution data for documentation, surveying, mapping and monitoring natural resources and man-made objects becomes more and more demanding, the UAVs are becoming more and more promising. Nowadays, UAVs can carry not only imaging but also non-imaging sensors, but such a platform for collecting imagery data are in a niche in geospatial technologies. The hardware costs are going down and down, while the advances in sensor and camera technologies, along with the availability of light and lifelong batteries, have made the mass production of UAVs possible.

UAVs for mapping purposes are nowadays mainly categorized as "fixed-wing" and "multirotor" devices. There are also helicopter-based UAVs. Fixed-wing UAVs fly faster and are suitable for covering larger areas but at smaller image scales. They usually have lower payload capabilities than the multirotor ones and, obviously, cannot hover over a target. In addition, they need some plane area for takeoff and landing. On the other hand, multirotor UAVs can usually have four to eight rotors and are capable of hovering and thus performing pinpoint photography. They are also capable of flying lower, thus allowing for larger image scales. With their increased payload capability, they may also be equipped with bigger DSLRs and, even, with small LiDAR systems. Multirotor UAVs are more complicated platforms than their fixed-wing counterparts, and consequently, are more demanding as far as their navigation and control are concerned.

All imaging UAVs are equipped with a GNSS receiver and an INS system in order to provide orientation and control while airborne. These devices also enable the UAVs to perform preprogrammed flights and take images at designated points in space. This flight planning may be performed in specialized software which usually accompanies the UAVs and may be run on a simple computer. The flight plan may even be realized on Google Earth, which is very convenient. Legislation on the other hand is very fuzzy and it varies from country to country, if there is one established. In the USA, drone-flying regulations vary from state to state. In the EU there is currently an effort to accept common rules for flying UAVs. In any case, the local authorities should always be informed about an imminent flight, which should under no circumstances interfere with normal air traffic.

2.4 Active Data Acquisition Methods

Accurate representation of objects, large and small, has been in the forefront of scientific interest for as long as the specialists felt the need for studying those objects. Two-dimensional representations using rules and techniques of projective and descriptive geometry have been common practice for centuries. It was from these 2D representations that three-dimensional information ought to be extracted. This task required special education, hard practice, skill and imagination. Nowadays these techniques have been largely replaced by digital scanning which is achieved using 3D scanners.

A 3D scanner is a device that records a real-world object or the environment to collect data on its shape and possibly its appearance (i.e. colour, material). The collected data can then be used to construct digital, three-dimensional models useful for a wide variety of applications. Digital scanning of objects has been common practice for more than two decades. Laser technology has been the flagship of this activity, but other means of acquiring 3D information of an object's surface have also been used widely. Modulated light scanners, non-contact passive scanners, photometric systems and silhouette scanners are the most known kinds of systems acquiring vast numbers of points describing the surface of interest. All these systems work at different rates, achieving various densities and providing different accuracies; hence, each one serves special needs in the market.

The final products of digital scanning methods are, of course, point clouds of varying densities and accuracies. Processing of these point clouds involves the implementation of a multitude of software and techniques, in order to produce 3D meshes, 3D surface models and, finally, 3D-rendered models of varying resolutions. Digital scanning has been used extensively in many applications, such as cultural heritage documentation, industrial applications and design, automotive industry, orthodontics and prosthetics, reverse engineering and prototyping, quality control and inspection and—of course—in the entertainment industry for the production of movies and video games (e.g. [21, 22]).

2.4.1 Scanners

2.4.1.1 Terrestrial Laser Scanners

Terrestrial laser scanners are devices that emit laser radiation and detect its reflection in order to probe an object or environment. Active scanners may use any kind of radiation, which may include light, ultrasound or X-ray. Laser scanners are also referred to as LiDAR scanners, from the acronym Light Detection and Ranging. These LiDAR scanners may be used to scan buildings, rock formations, etc. in order to produce a point cloud, i.e. millions of points in 3D space and from that a 3D model.

The device can aim its laser beam in a wide range: its head rotates horizontally, a mirror flips vertically. The laser beam is used to measure the distance to the first object on its path. Terrestrial laser scanners are distinguished into three main categories: time-of-flight scanners, which may use the pulse; phase-shift technique to measure the distance; and triangulation scanners.

Time-of-flight 3D laser scanners are active devices that use laser light to probe the subject. At the heart of this type of scanner is a time-of-flight laser source and a rangefinder. The device determines the distance of a point by timing the round-trip time of a pulse of light. Since the speed of light c is known, the round-trip time determines the travel distance of the laser beam, which is twice the distance between the scanner and the point which reflected it. If t is the round-trip time, then distance is equal to:

$$(c \cdot t)/2.$$

The accuracy of a time-of-flight 3D laser scanner depends on how precisely it can measure the t time. Highly accurate clocks are operating in today's laser scanners, which are able to measure time to a few picoseconds. It is pointed out that the time taken for light to travel 1 mm is 3.3 picoseconds.

The laser rangefinder only detects the distance of one point in its direction of view. Thus, the scanner scans its entire field of view one point at a time by changing the rangefinder's direction of view to scan different points. The view direction of the laser rangefinder can be changed by either rotating the rangefinder itself or by using a system of rotating mirrors. The latter method is commonly used because mirrors are much lighter and can thus be rotated much faster and with greater accuracy. Typical time-of-flight 3D laser scanners can measure the distance of 10,000–100,000 points every second. Pulse scanners can achieve an accuracy of 3–5 mm and may have a range of a few hundred metres up to a couple of kilometres, depending on the power of the laser source.

Phase-shift technology is a variation of the above described pulse method, by which the phase difference between the emitted and the returned radiation is determined. In this way the device is able to determine the distance to each measured point to an accuracy of 2–3 mm and collects far more points per second. Today's phase-shift scanners may reach a recording rate of one million points per second, but their range is confined to a couple of hundred metres.

Triangulation laser scanners use a slightly different method for determining the relative position of the collected points in 3D space. The triangulation laser scanner casts a laser beam on the object and exploits a camera to look for the location of the laser dot. Depending on how far away the laser strikes a surface, the laser dot appears at different places in the camera's field of view. This technique is called triangulation because the laser dot, the camera and the laser emitter form a triangle. The length of one side of the triangle—the distance between the camera and the laser emitter—is known. The angle of the laser emitter corner is also known. The angle of the camera corner can be determined by looking at the location of the laser dot in the camera's field of view. These three pieces of information fully determine the shape and size of the triangle and gives the location of the laser dot corner of the triangle. In most cases, a laser stripe, instead of a single laser dot, is swept across the object to speed up the acquisition process. Triangulation laser scanners have very limited range capability, i.e. at the order of a few metres, but they are very accurate in determining the points in space. They may provide accuracies to the order of micrometres.

The time-of-flight scanner's accuracy can be disrupted when the laser hits the edge of an object because the information that is sent back to the scanner is from two different locations for one laser pulse. The coordinate relative to the scanner's position for a point that has hit the edge of an object will be calculated based on an average and therefore will put the point in the wrong place. When using a high-resolution scan on an object, the chances of the beam hitting an edge are increased, and the resulting data will show noise just behind the edges of the object. Scanners with a smaller beam width will help to solve this problem but will be limited by range as the beam width will increase over distance. Software can also help by determining that the first object to be hit by the laser beam should cancel out the second.

At a rate of 10,000 sample points per second, low-resolution scans can take less than a second, but high-resolution scans, requiring millions of samples, can take minutes for some time-of-flight scanners. The problem this creates is distortion from motion. Since each point is sampled at a different time, any motion in the subject or the scanner will distort the collected data. Thus, it is usually necessary to mount both the subject and the scanner on stable platforms and minimize vibration. Using these scanners to scan objects in motion is very difficult. When scanning in one position for any length of time, a slight movement can occur in the scanner position due to changes in temperature. If the scanner is set on a tripod and there is strong sunlight on one side of the scanner, then that side of the tripod will expand and slowly distort the scan data from one side to another. Some laser scanners have a level compensator built into them to counteract any movement of the scanner during the scan process [23, 24].

2.4.1.2 Structured Light Scanners

An alternative to the mostly known and market-dominating laser scanners are structured light scanners. Structured light 3D scanners project a pattern of light on the object and detect the deformation of the pattern on the object. They are basically non-contact optical systems, based almost entirely on the principles of photogrammetry in order to transform image pairs to surface information. They are able to achieve information of very high density and of very high accuracy.

Several practical applications of the system are presented, in order to demonstrate its range of applicability. Special interest is given in processing aspects for the creation and visualization of detailed photorealistic 3D models. Various well-known open issues in the related processes are identified, and the respective solutions and improvements in the workflow pipeline brought by the employment of this technology are highlighted. The software used for processing the data acquired by structured light scanners is briefly described, and high-resolution visualizations of submillimetre accuracy for each case study are presented and assessed based on completeness, accuracy and ease of processing. The practical results are discussed and evaluated based on the experience gained through these applications.

As already mentioned, structured light 3D scanners project a pattern of light on the subject and detect the deformation of the pattern on the object's surface. The pattern may be one dimensional or two dimensional. An example of a one-dimensional pattern is a line. The line is projected onto the subject using either an LCD projector or a sweeping laser. A camera, offset slightly from the pattern projector, records the shape of the line at an angle α, and a technique similar to the triangulation principle is used to calculate the distance of every point on the line. In the case of a single-line pattern, the line is swept across the field of view to gather distance information one strip at a time.

An example of a two-dimensional pattern is a grid or a line strip pattern [21]. A camera is used to record the deformation of the pattern, and a fairly complex algorithm is used to calculate the distance at each point in the pattern. One reason for this complexity is ambiguity. The advantage of structured light 3D scanners is speed. Instead of scanning one point at a time, structured light scanners scan multiple points or the entire field of view at once. This reduces or eliminates the problem of distortion from motion. Some systems that employ such methods enable the scanning of moving objects in real time. In most cases such systems have a relatively narrow field of view that may range from a few centimetres to a couple of metres, based on the components of the system and the calibration process.

Zhang and Huang [25] developed a real-time scanner using digital fringe projection and phase-shift technique, a somewhat different structured light method. The system is able to capture, reconstruct and render the high-density details of the dynamically deformable objects, such as facial expressions, at 40 frames per second.

A typical structured light scanner system comprises low-cost off-the-shelf hardware. Two digital SLR cameras of 12 MP or alternatively two machine vision cameras mounted on a rigid base take up the role of image pair acquisition. A DLP projector is used to project the necessary structured light alternations, and the whole system, including supportive tripods, is operated through a standard laptop running the usually proprietary software. The distance between the cameras, i.e. the base, may be varied, according to the size of the object of interest and to its distance from the cameras. The system is driven via a laptop with proprietary software that carries out the required processing for the structured light data (Fig. 2.9). This software takes care of the camera and projector's smooth coordination. It provides for the necessary setup calibration, which includes both camera geometry parameters and also relative positioning of the image acquisition set with the help of a suitable test field, most usually a checkerboard.

The fact that some of these systems employ two cameras is clearly an advantage. The workflow usually requires a calibration sequence, and after that it is ready to acquire the data for producing the 3D information. The calibration procedure determines both the interior orientation parameters of the camera(s) and their relative positions and the scale of acquisition. For this purpose, a custom calibration board, a simple chequered board, is imaged at various angles by both cameras

Fig. 2.9 The main components of the SL2 scanner

Fig. 2.10 SL2 scanner calibration

(Fig. 2.10). The software then calculates the various parameters and the system is ready for use. A series of calibration boards with different physical and square sizes is usually provided, in order to cover various taking distances. The larger the distance, the bigger the calibration board obviously necessary. The calibration procedure theoretically needs a few minutes to be completed, but in practice it is proven that it takes something between 20 and 40 min for each new setup, depending on the ambient conditions, i.e. taking distance and lighting. After the setup calibration, the software drives the cameras for the main data acquisition phase.

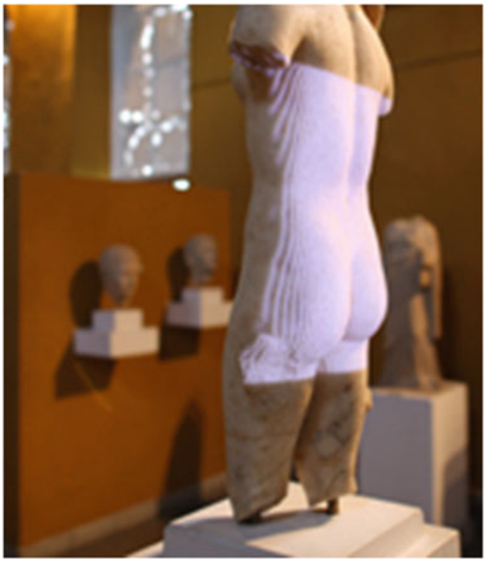
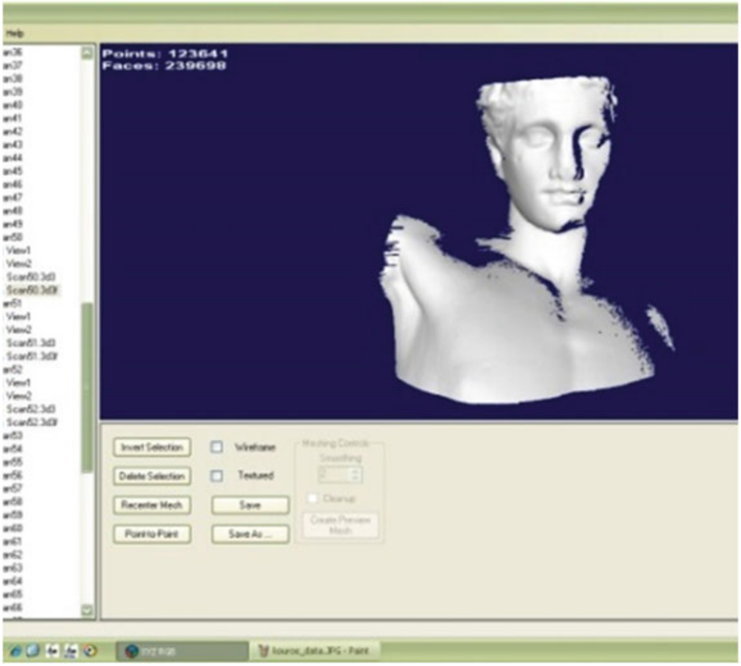


Fig. 2.11 Projected structured light during data acquisition

Scanning with such systems actually involves the acquisition of several consecutive image pairs; alternating patterns of light are projected onto the object in sequence (Fig. 2.11). These patterns are alternating black and white stripes with decreasing width. Based on the distortion of these stripes on the object as they are imaged on both images of the stereopair, the software later calculates a triangular mesh of the object's surface, on which the texture may be projected. The system calculates depth by the exploitation of the distortion of these patterns on the surface of the object, following the triangulation principle, only in this case two cameras are employed. The result is a dense (up to 150 μm) mesh of triangles, with points on the objects surface (Fig. 2.12).

Once the system has been calibrated, scanning is fast and reliable. However, the results are highly dependent on the behaviour of light on the surface of the object, and great care should be given to the imaging parameters of the cameras. The use of suitable polarizing filters both for the projector and for the cameras is often recommended.

Depending on the complexity of the object's surface, on its size and on the required density and final accuracy, a considerable number of individual scans may be necessary to cover the object. Using 3D processing software that is usually included in the bundled software, mesh registration is very fast, precise and easy. However, further processing for visualization or rendering requires use of other more specific software, such as 3D Studio Max, Geomagic and Maya.



```
Points: 123641
Faces: 239698
```

Fig. 2.12 The resulting 3D mesh

2.4.1.3 Range Cameras

A time-of-flight (TOF) camera, usually referred to as a range camera, is a range-imaging camera that basically measures the TOF of a light signal between the camera and each point of the object and thus actually resolves the distance based on the known speed of light. Such a device measures the direct TOF required for a single laser pulse to leave the camera and come back into the focal plane. In the "trigger mode", the 3D images captured, image complete spatial and temporal data, recording full 3D scenes with single laser pulse.

Nowadays, several different technologies for range-imaging flight cameras have been developed. A TOF camera delivers a range image and an amplitude image with infrared modulation intensities at video frame rates. As reported in different studies [26–28], the distance measurements of range-imaging cameras are influenced by some systematic errors, which can be managed by using different distance error models.

On the other hand, in the area of cultural heritage, Rinaudo et al. [29] used SR-4000 camera (Fig. 2.25, first from left) in a standard survey procedure to generate a realistic 3D model, applying at the same time a self-calibration model on the captured point clouds they had to compare. In addition, a high-resolution digital image from a calibrated camera was used to colour the 3D model by using the radiometric information extracted from the image. They concluded that the high sampling rate of the SR-4000 camera allows conceiving a possible use of the range-imaging camera to record data on objects like windows, rooms or statues. The same authors, Chiabrando et al. [27] perform a relevant work for metric surveys. In this work a systematic investigation of the influence of object reflectivity on the range camera distance measurement accuracy and precision was performed, which outlined that the object reflectivity strongly influences the distance measurement precision. Nevertheless, the worse measurement precision of 5 mm obtained is still acceptable for specific applications. Considering a comparison between SR-4000 data and LiDAR data on an architectural element, they demonstrated the high potential of range-imaging cameras for metric surveys of architectural elements and for 3D object reconstruction. These sensors do not seem to be mature yet for use in high-accuracy, demanding applications. However, they definitely have some potential, and their technological evolution should be closely followed.

2.5 Geometric Documentation Examples

In this section, two characteristic examples are presented from projects carried out by the authors. The aim is to show real practical implementations of the data acquisition methods presented in this chapter. It is not important to present details but to show the results and what may be done with them.

The first example refers to the geometric documentation of four historic buildings, namely, the Byzantine churches of Mount Troodos in Cyprus. They are complex and challenging structures, especially as far as their interior decoration with frescoes is concerned. The second example refers to smaller cultural heritage objects, namely, two ancient vessels displayed in the archaeological museum in Athens. The challenge, in this case, is their size and the fact that they should be handled with utmost care.

2.5.1 The Geometric Documentation of Byzantine Churches in Cyprus

In this section some characteristic applications of ICT for cultural heritage will be presented in order to show their contribution and also their evolution. All examples are concerned with the documentation of the Byzantine churches of Mount Troodos in Cyprus.

In the central area of Mount Troodos in Cyprus (Fig. 2.13), there are ten Byzantine churches, unique specimens of Byzantine architecture and religious art dating from the eleventh to the fourteenth century. These ten churches (Fig. 2.14) have been inscribed in the WHL of UNESCO since 1985. The criteria for that were their unique architecture and also their wonderful frescoes (Fig. 2.15), which constitute a “special document of cultural tradition”. About one million visitors are attracted each year to these churches. They are:

Saint Nikolas of Stegi in Kakopetria
Saint John the Lambadistis in Kalopanagiotis
Lady Mary Forviotissa of Asinou in Nikitari
Lady Mary of Arakas in Lagoudera
Lady Mary of Moutoullas
Archangel Michael in Pedhoulas
The Holy Cross in Pelendri
Lady Mary of Podithou in Galata
The Cross of Agiasmati in Platanistasa
The Transfiguration of the Saviour in Paliochori

The Geometric Documentation of the Troodos Churches is already underway since 2005 as an effort in collaboration between the Laboratory of Photogrammetry of National Technical University of Athens and the HTI of Nicosia, initially, and later with Cyprus University of Technology.

During the past 11 years, four out of the ten churches have been geometrically documented. Every time with different methodology and always with the latest and most advanced instrumentation for collecting and processing the data [30–33]. In Table 2.4 all important details of these projects can be seen.

By studying Table 2.4, it is apparent how the evolution of the methods has influenced the instrumentation as well as the time necessary for collecting and processing the raw data. The geodetic instrumentation has not experienced a dramatic progress. The use of the imaging total station has perhaps enabled the correct identification of the measured points, thus avoiding gross errors. During these last 10 years, the 3D scanning technology has advanced a lot. However, the high cost of the newer and more modern scanners is prohibiting the constant update of the related instrumentation. Hence, the most important change is identified in the photographic instrumentation. The resolution increase becomes apparent, but the sensor size also plays an important role for the final quality of the products. In parallel, the modernization of the software is perhaps the main source of improving the results and saving processing time. This modernization is based on the overwhelming progress of computer power and on the development of more efficient algorithms. The main algorithm which brought a big change is the incorporation of the structure-from-motion (SfM) procedure, which makes use of the computer power of newer processors in order to determine the orientation of the images and also to achieve the object reconstruction imaged in a series of densely overlapping digital images. The result of these algorithms is equivalent, if not better, to the one from terrestrial laser scanners. In addition, these pieces of software are in a position to produce textured 3D models using colour from the digital images.

Fig. 2.13 The area on Troodos mountain where the ten Byzantine churches included in the UNESCO WHL are situated (Source: Google Earth)

Fig. 2.14 Specimens of the architecture of the Byzantine churches of Troodos Mountain

Fig. 2.15 Specimens of the frescoes of the Byzantine churches of Troodos Mountain

Table 2.4 Comparative presentation of the basic characteristics of the geometric documentation methods

	Lady Mary of Asinou	Lady Mary of Podithou	Holy Cross	Archangel Michael
Date	2005	2008	2011	2014
Instrumentation				
Geodetic	Topcon GPT-3003 reflectorless total station	Pentax R-323NX reflectorless total station	Leica TPS 1200 reflectorless total station	Topcon 7003i Imaging station
3D scanner	HDS/Cyrax 2500	HDS/Cyrax 2500	Scanstation 2	Scanstation 2
Image acquisition	Canon MII 8M pixel	Canon MII 8M pixel	Canon M III—21Mp full frame	Canon M III—21Mp full frame
Other			Z-scan, TheoLT	
Software	ARCHIS by SISCAM SSK of Z/I Imaging	PhotoModeler	RDF Image Master	Image Master, PhotoScan
Members of the team	3	4	4	3
Duration of works				
Fieldwork (days)	14	10	7	5
Processing (months)	8	7	6	5
Results	Plan, roof plan, outside facades, sections (with orthophotos)	Plan, roof plan, outside facades, sections (with orthophotos)	Plan, roof plan, outside facades, sections (with orthophotos)	Plan, roof plan, outside facades, sections (with orthophotos)
Documentation products	3D model	3D model	3D model	3D model

The production procedure of the contemporary geometric documentation products follows some basic steps, which in brief are the measurements of three-dimensional points in space. This may be done in three ways:

- Using geodetic methods, which collect specifically selected points with great accuracy
- Using scanning methods, usually based on laser technology, which collect a huge number of non-controlled points with lower accuracy but in certain cases with the ability of assigning colour information to them
- Using dense image matching methods on digital images, which determine a large number of points with high accuracy including colour information

From these points, and also from the point cloud, there is the possibility of producing the section lines of various vertical and horizontal sections, which were decided to be the geometric documentation products of the monument. However, the details, and those in image form in particular, demand the production procedure of an orthophoto (Fig. 2.16). This may be done the classic way from the images and the description of the surface, i.e. the point cloud, and also directly from the point cloud using specialized software [34, 35].

The production of the 3D model is rather complicated and demands a time-consuming procedure. From the point cloud points, a triangular mesh should be produced and from that the surface of the object. In this procedure one should make sure that there are no residual errors on the surface, such as holes, wrongly oriented triangles, which occurs very often. Afterwards, the texture information should be identified on the digital images available. This action is in essence a mapping of the desired information on the object's surface. This results in a realistic 3D model with texture and colour, which may serve different needs (Fig. 2.17).

The use of these 3D models is not completely clear yet. Other researchers desire to have the 3D model just for visualization purposes, others desire to publish it online, others use them for educational and touristic purposes, while others would like to use them for metric purposes, i.e. they extract metric information from them. It is obvious that all these uses demand 3D models of different specifications. Hence, the provider and technology expert should understand the user's needs, in order to provide him with the suitable 3D model each time.

It becomes apparent from the above that the implementation of contemporary information and communication technologies (ICT) during the last decades has had a positive influence on the curation of cultural heritage. This positive influence is identified both on the required time, on the accuracy of the final products and also on the multitude of alternative products which are possible nowadays. The final users are still a little reluctant to accept new technologies and sometimes understand their usefulness. Hence, it is imperative that the users get acquainted with them, but, at the same time, the providers should show patience for understanding the needs of the users in order to provide the most suitable product each time. This mutual effort requires interdisciplinary approach to the problem.

2.5.2 The Geometric Documentation of Ancient Vessels

Besides the display of the findings, modern museums organize educational programmes which aim to experience and knowledge sharing combined with entertainment rather than to pure learning. Towards that effort, 2D and 3D digital representations are gradually replacing the traditional recording of the findings through photos or drawings. This example refers to a project that aims to create 3D textured models of two lekythoi that are exhibited in the National Archaeological Museum of Athens in Greece; on the surfaces of these lekythoi scenes, the adventures of Odysseus are depicted. The creation of accurate developments of the paintings and of accurate 3D models is the basis for the visualization of the adventures of the mythical hero.

The data collection was performed by using a structured light scanner consisting of two machine vision cameras used for the determination of the geometry of the

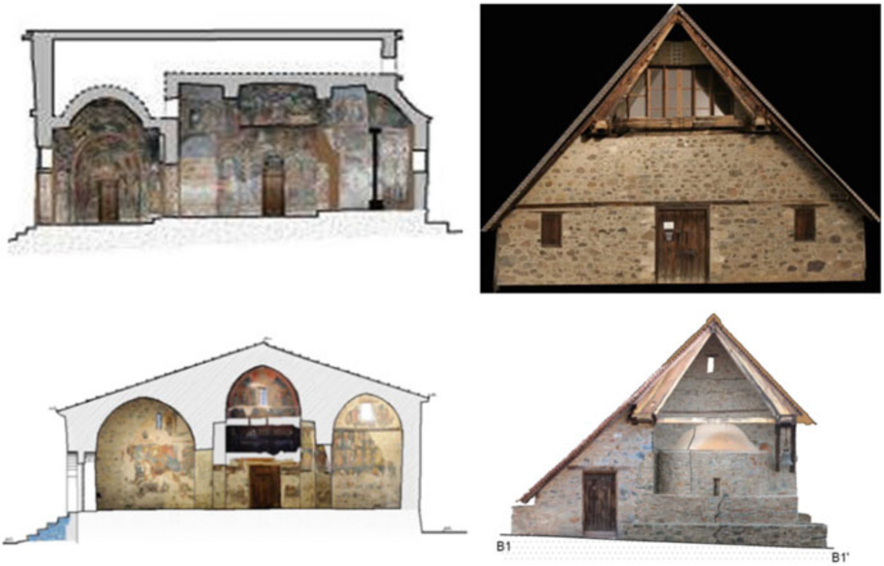


Fig. 2.16 Selected sections with orthophotos of the four Byzantine churches

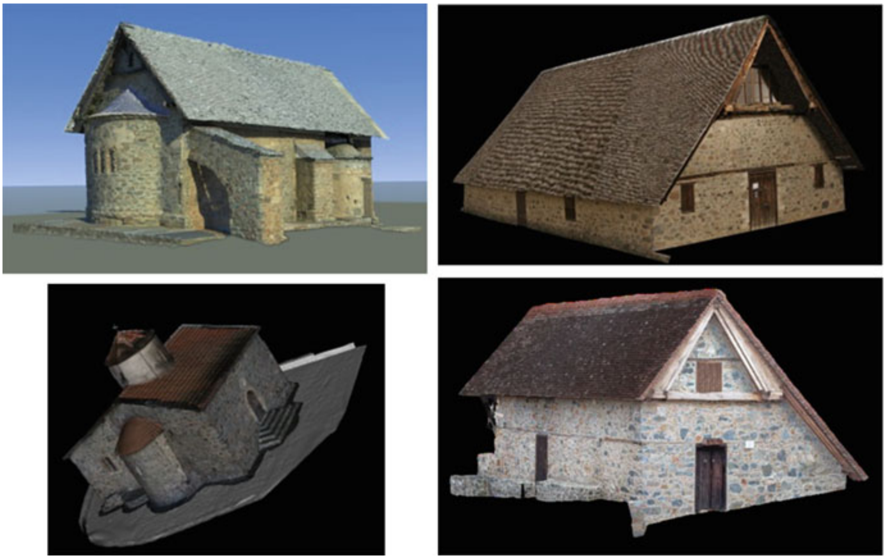


Fig. 2.17 3D models of the four Byzantine churches

object, a high-resolution camera for the recording of the texture and a DLP projector. The creation of the final accurate 3D-textured model is a complicated and tiring procedure which includes the collection of geometric data, the creation of the surface, the noise filtering, the merging of individual surfaces, the creation of a *c*-mesh, the creation of the UV map, the provision of the texture and, finally, the general processing of the 3D-textured object. For a better result, a combination of commercial and in-house software developed for the automation of various steps of the procedure was used. The results derived from the above procedure were especially satisfactory in terms of accuracy and quality of the model. However, the procedure was proved to be time consuming, while the use of various software packages presumes the services of a specialist [36].

The 3D recording and digital processing of the two lekythoi aim to support the production of an educational movie and some other relevant interactive educational programmes for the museum. The creation of accurate developments of the carvings and of accurate 3D models is the basis for the visualization of the adventures of the mythical hero.

The technique used here for data acquisition belongs to the passive methods. The data collection was performed using an XYZRGB® structured light scanner. It consists of two machine vision cameras, used for the determination of the geometry of the object, and of a high-resolution camera, used for the recording of the texture, plus a DLP projector. The use of two cameras for the determination of the geometry of the object facilitates the procedure since neither the correlation of the pixels of the projector with the pixels of the camera nor the knowledge of interior orientation is required. The representations need to be of good quality and the data need to be of high accuracy to facilitate the production of further product representations (e.g. developments), which help in a better understanding of the story that is painted or carved on a finding (e.g. a vessel or a decorative part of an object).

Two lekythoi (cosmetic vessels) exhibited at the National Archaeological Museum of Athens were selected: a bigger one with a height approximately up to 30 cm (Fig. 2.18, left) and a smaller one with a height approximately up to 20 cm (Fig. 2.18, right). On the surface of these two vessels, scenes of the adventures of Odysseus are depicted. These vessels are dated back to the fifth century BC and were discovered in the region of Athens, Greece. They are painted in dull red and black colours.

For the acquisition of the 3D data, the SL2 model of XYZRGB structured light scanner was used (Fig. 2.19). It consists of the following components:

- A Canon 450D digital SLR 12MP high-definition camera
- Two uEye 5MP machine vision cameras
- An InFocus IN35W DLP projector
- A laptop running the appropriate software
- A calibration board, with known dimensions

The three cameras are mounted on a rigid base. The distance between the cameras may vary according to the object scanned, and it is usually set up to 1/3 of the scanning distance. The maximum density capability equals to 150 μm and the maximum precision to 50 μm, according to the manufacturer.

The calibration affects the precision of the extracted point cloud. The calibration board is set in approximately 11 different positions, including change in position

Fig. 2.18 The two lekythoi, with the adventures of Odysseus depicted on their surface

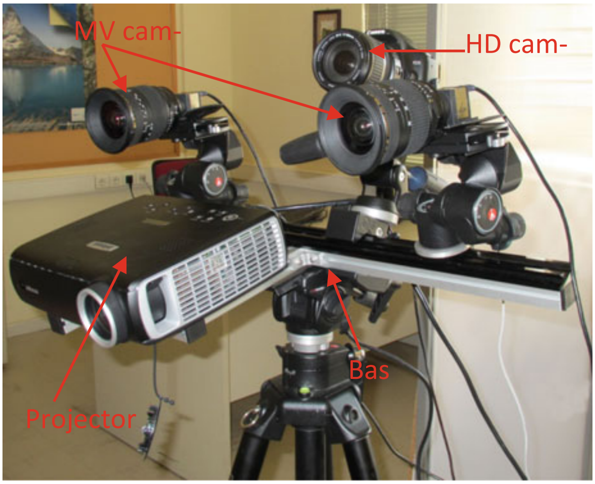


Fig. 2.19 The SL2 model of XYZRGB structured light scanner

and rotation. Performing plane-based calibration, the interior orientations of the three cameras and the relative (scaled) orientations between them are computed.

During the procedure of scanning, the relative position between the three cameras has to remain unchanged. The scanning procedure is fast and reliable. However, for a successful result, the imaging parameters of the cameras have to be set correctly in the scanning software, according to object's colour, material and lighting conditions.

The uEye software is responsible for the determination of the suitable imaging parameters of the cameras, so as to acquire data with best quality. Some of these well-known parameters are pixel clock and exposure, which are related to the refresh rate of the pixels on the screen and the amount of light allowed to fall on the photographic sensor.

For the scanning procedure, the software provided by the company XYZRGB® is used. The ideal number of scans varies according to the size and complexity of the object and also according to the desirable accuracy and density of the final product. Attention should be paid so that the scans will have adequate overlap. In this application, 41 scans were necessary for the first vessel and 39 scans for the second one. The result of each scan is a point cloud. The software gives the opportunity to test the quality of the data that will be acquired before each scan. Each point cloud is triangulated into a mesh, which is easier to handle, using Delaunay triangulation. The image from the high-resolution camera ensures that the mesh is textured. The results from each individual scan are the mesh, which is exported in OBJ format for further processing, and an image in JPG format, which is responsible for the texture information.

The products of the scanning procedure were processed using various software packages for the production of the final accurate 3D-textured model of the vessel. For a better result and automation of various steps of the procedure, a combination of (commercial and in some cases in-house) software is made. In the following, the individual steps of this procedure and the used software are given.

First the meshes were inserted in Geomagic Studio for the hole filling and the registration (merging) of the individual meshes for the creation of the final surface, as each mesh refers to a different local system. The most popular algorithm for the registration of the meshes, which was also used here, is the ICP. Selecting at least three common points between the two meshes, initial values are calculated for the transformation, which are then optimized. Having completed the registration of all meshes, the final surface is processed as a whole, and all the individual meshes are extracted separately in OBJ format,[6] so as to be georeferenced (Fig. 2.20).

The texture of the final 3D model relies on the procedure of texture mapping. To generate a texture map, the 3D model has to be simple enough due to restrictions imposed by computer memory limitations. As the surface of the lekythoi is really complex and the 3D model is detailed and precise, it is absolutely necessary to be simplified. Thus, a new surface is created, called constrained mesh (c-mesh). This surface is composed of quadrangles or triangles. The specific procedure was implemented in the GSI Studio software (a product of the XYZRGB Company).

The UV map, that is actually offering the texture to the 3D model, is a kind of development of the created constrained mesh. Each vertex of the 3D model, defined by X, Y, Z coordinates, is projected onto this two-dimensional image (texture map)

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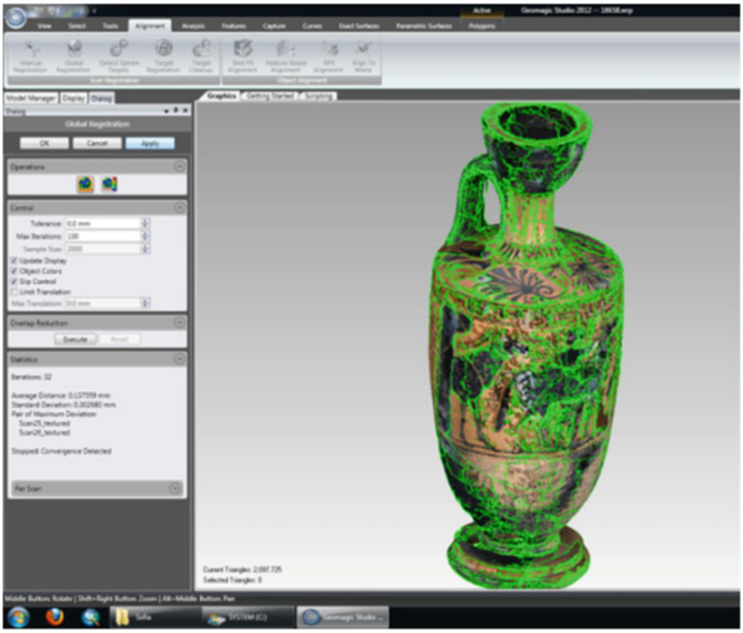
[6] http://en.wikipedia.org/wiki/Wavefront_.obj_file



Tolerance: 0.0 mm
Max Iterations: 100
Sample Size: 2000
☑ Update Display
☑ Object Colors
☑ Slip Control
☐ Limit Translation
Max Translation: 0.0 mm

Iterations: 32

Average Distance: 0.137559 mm
Standard Deviation: 0.302680 mm
Pair of Maximum Deviation:
Scan25_textured
Scan26_textured

Stopped: Convergence Detected

Fig. 2.20 The surface of a lekythos after the registration of all individual meshes

and is now defined by *U*, *V* coordinates.[7] The creation of the UV map was performed in the Deep UV software of Right Hemisphere®. This procedure may be done either automatically or manually. The shape of the vessels does not comply with any developable surface, and thus the automated procedure has created a complicated texture map hard to use (Fig. 2.21). Thus, the texture map was extracted manually, by selecting parts of the surface with common characteristics (complexity, curvature) and deciding in which developable surface it adjusts better (cone, cylinder).

The next step is to provide the texture map with the right colours. For this procedure, the georeferenced meshes and the image of each scan and the constrained mesh were inserted in the 3D Studio Max software by Autodesk. The result is a texture map with colour, containing the information from each scan. This step results in many texture maps; the number of texture maps equals the number of individual scans, acquired during the field work. However, for the texture of the final surface, only one texture map must be used. Thus, all the individual texture maps are composed and turned into the final texture map using the Photoshop CS5® software (Fig. 2.22).

For the visualization of the final product in any software capable of managing 3D information, the OBJ file of the constrained mesh, the final texture map (a JPG file)

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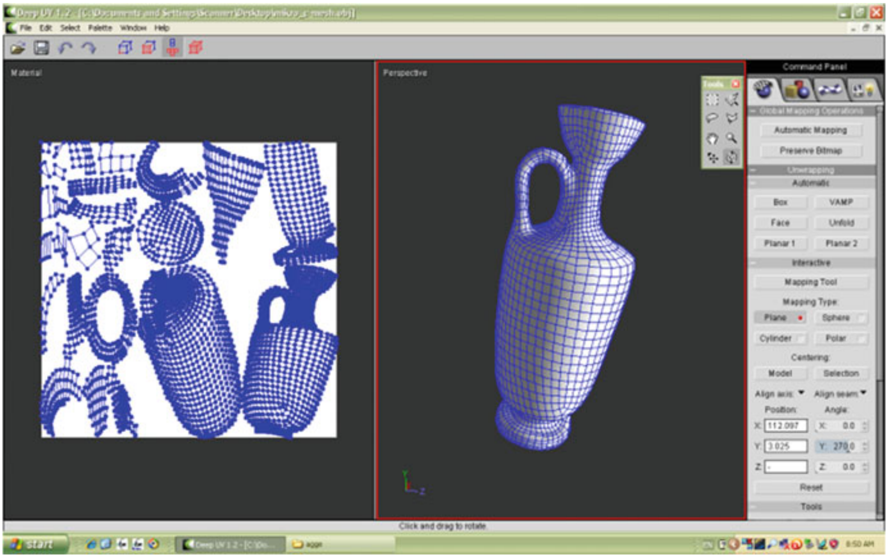
[7] http://en.wikipedia.org/wiki/UV_mapping



Position: X 112.097, Y 3.025

Angle: X 0.0, Y 270.0, Z 0.0

Click and drag to rotate

Fig. 2.21 Automated creation of UV map (2D texture map) through the algorithms of the Deep UV software

Fig. 2.22 The final texture map of the smaller lekythos

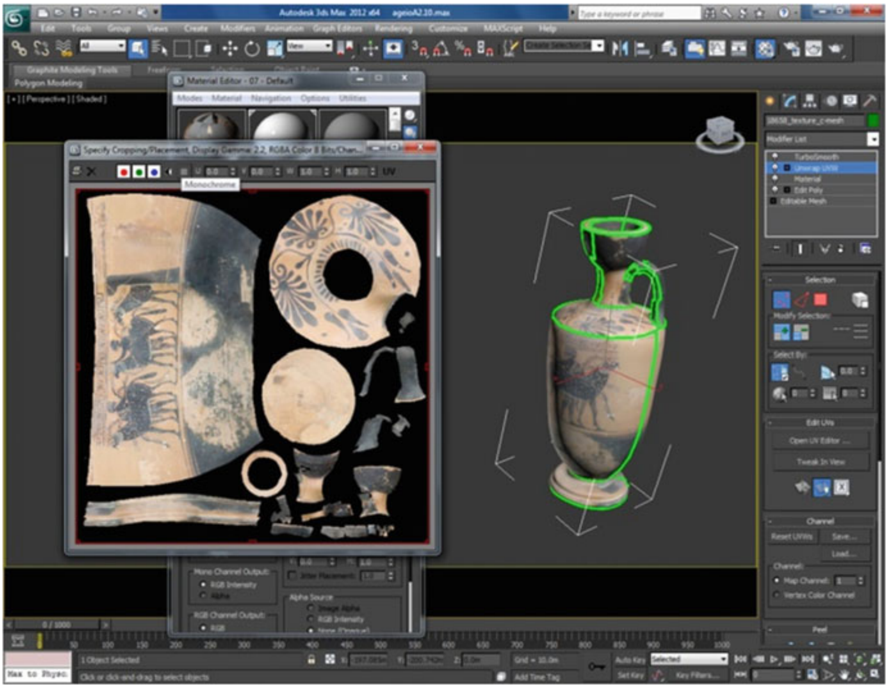


Fig. 2.23 Final processing of the bigger lekythos, a 3D-textured model

and an MTL file are needed. The MTL file contains the name of the material (in this case the texture map) and its properties.[8] In this project, the final optimization of the 3D-textured model was implemented in 3D Studio Max software, where radiometric and smoothing interventions were made (Fig. 2.23).

In addition, as a by-product of the processing, the development of the main body of each lekythos is created, the surface of which is close to a cylinder, and it shows the representation of an adventure of Odysseus. The developments are shown at the lower part of Figs. 2.24 and 2.25 for both lekythoi. This product is very useful for the visualization of the story of each myth as it represents in an easily understandable way (2D image) the scene that decorates all the (almost cylindrical) surface of the vessel.

For the processing of the scanned data, a combination of software was used; each step of the procedure was done using different software (XYZRGB, Geomagic Studio, GSI Studio, Deep UV, Photoshop, 3D Studio Max). The selection was made after several thorough trials using various software that can execute each individual step of the process and by determining the appropriate parameters for their best operation. Many of the above procedures were repeated several times in order to

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[8] http://people.sc.fsu.edu/~jburkardt/data/mtl/mtl.html

Fig. 2.24 The final 3D model (*up*) and the development of the texture map of the carving (*bottom*) of the bigger lekythos

have an acceptable result. That way, some very good results have been obtained in terms of accuracy and quality of the final products (developments and 3D-textured models), but the process is time consuming, and the quality of the results is up to the user's experience. In addition, particular attention should be given to fieldwork, where the definition of the scan parameters play a crucial role for proper collection of data, which facilitates continuity and correct processing and workflow.

In general, the hardware and the processing of the selected 3D data provide satisfactory results regarding the geometry of the final product, making good use of the capabilities of the structured light scanner.

A disadvantage of the used method is the step of simplifying the surface, so as a suitable texture can be attributed to the 3D model. It is advisable that this step be carried out manually, so the user can decide the rate of simplification. The final results seem to depict the object with high fidelity, but the problem is the lack of a quantitative criterion for checking the rendering texture.

The procedure followed in this project proved to be the most appropriate method for the creation of the 3D-textured models of archaeological findings. Its

Fig. 2.25 The final 3D model (*up*) and the development of the texture map of the carving (*bottom*) of the smaller lekythos

application on the two lekythoi gave very good results both in terms of accuracy and quality. However the low degree of automation of the process may create a problem as the final product depends on the experience and the knowledge of the user.

Also, a general conclusion is that each geometric documentation process of an archaeological object has different requirements, and the most appropriate method to be followed must be studied examining numerous factors. The creation of accurate 3D-textured models is a field with many opportunities for future research.

However, the three-dimensional-textured models and their 2D developments are an attractive solution to the presentation of archaeological findings in an effort to create an attractive educational tool, which may help kids and students to participate actively during their visit to an archaeological museum. The museum becomes a cosy and intimate space, a place of learning through play. Children are encouraged to observe, to think, to express themselves and to act. Also the ability to view 3D models via Internet is another important area of action to be developed in museums. An interactive museum visit converts visitors to active participants of the museum process. The hidden information is the additional material that is stored on the computer, which is revealed and activated through an interactive application, stimulates interest and activates the processes of participation and guest's choice.

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