3D SCANNING

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3D scanning as a technological procedure is aimed at collecting information on the shape and colour of the object scanned. The acquired data help build a basis for the construction of digital, three-dimensional models useful for a wide variety of interpretative purposes. Currently, there are a lot of different technologies and 3D scanning devices available, each one coming with its own limitations, advantages and costs. Prime properties of the 3D scanning solution are its ability to effectively capture digital description of the objects and meet the required level of accuracy and data clarity. According to the source, applied scanning, laser scanning and structured light scanning can be distinguished.[1] The three principle types of scanning technology include Time-of-Flight (TOF), Phase-Shift (PS) and Triangulation-based systems. Scanning technology is connected to other system factors, including the acquisition distance, the acquisition rate and the data resolution/accuracy.

There is a wide range of 3D scanning technologies available for different items within the sphere of cultural heritage, ranging in size from small archaeological finds to large structures. There have been many studies that illustrate how 3D scanning, implemented in the protection of cultural heritage, generates excellent results, both in terms of speed and of accuracy. Until now, a lot of large scanning projects in the field of cultural heritage management and archaeological research have demonstrated the relevance of this method as a modern and, in many cases, fundamental documentation practice.

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[1] As a unique category, image-based scanning should be mentioned. Formerly, it used to be defined as 3D photogrammetry, but this is not a proper term.

LASER SCANNING

3D laser scanning is a non-destructive, non-contact method of capturing data that can be used for rapid and accurate creation of three-dimensional files, for archiving and digital manipulation. A 3D laser scanner emits a narrow laser beam that hits a target object, gathering millions of closely spaced measurements in a matter of minutes. These scanned measurements are put together and grouped into compressed point cloud databases, which can be processed to generate a 3D dense representation of the object (Arias et al. 2005; Yastikli 2007; Cheng et al. 2015).

In the most general terms, 3D laser scanning, also referred to as 3D digitising, entails the utilization of a three-dimensional data acquisition device for acquiring a multitude of X, Y and Z coordinates (points) + their RGB values. Furthermore, returning distance signals generate intensity information registered for each of the points. The intensity – often called 'the fourth dimension' – is a very useful parameter for visual enhancement of various architectural features, especially in the dense and complex point clouds (Staiger 2003). Each measured point is thus precisely defined in space, in a global or local coordinate system, with X, Y, and Z coordinates. The collection of all these points is defined as a 'point cloud'. The typical file format for point cloud data contains the X, Y and Z (possibly + RGB and intensity) values for each point, or a polygonal mesh representation of the point cloud (Slob, Hack 2004).[2]

Laser light is coherent, which means that a laser beam can propagate over long distances and can be focused to very small spots. Laser light may be visible, but most lasers actually emit in other spectral regions, in particular the near-infrared region, which human eyes cannot perceive. The first working laser was demonstrated in May 1960 by Theodore Maiman at Hughes Research Laboratories.[3] Although laser scanning was developed in the 1960s, it was not used for surveying structures until the late 1990s (SurvTech Solutions 2015). So far, laser scanning has proven to have an essential role in large scale cultural heritage projects as it provides a highly useful tool for global monitoring and damage detection (Pieraccini et al. 2001).

Airborne laser scanning (LiDAR)[4]

Airborne laser scanning (LiDAR = acronym for 'Light detection and Ranging', also LIDAR) is a scanning technique for capturing data on the features of, and objects on, the surface of the earth. It is an important data source in environmental studies, since it is capable of mapping topographic height and the height of objects on the surface to a significant vertical and horizontal accuracy, and over large areas. Airborne laser scanning is an active remote sensing technology able to rapidly collect data from vast areas. The resulting data-set can be used as a base in digital surface and elevation models. Airborne laser scanning is often coupled with airborne imagery; therefore, the point clouds and images can be fused together, thereby increasing the quality of the final 3D product – the high-quality 3D representation of a landscape (Vosselman, Maas 2010).

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[2] At present, there are plenty of file formats determined for point cloud data storage (e.g. ASCII, PLY, LAS/LAZ, etc.).

[3] https://en.wikipedia.org/wiki/Theodore_Harold_Maiman.

[4] LiDAR *per se* represents a substantial topic, thus we here provide a very brief outline.

Terrestrial laser scanning

Terrestrial laser scanners (TLS) are positioned directly on the ground, or on a platform placed on the ground, and are normally mounted on a tripod. TLS is, in its essence, an improved version of the laser tachometric measurement toolkit (the so-called total station) that is based on the combination of distances and angles measured from a fixed point. Tachometric laser scanners digitise objects of interest with a frequency of 1000 Hz or higher. Each point is measured per one oblique distance and, additionally, two orthogonal angles are measured (Vosselman, Maas 2010). Most TLS are long-range devices (see below) used for 3D documentation of large landscape areas or complex structures. Nowadays, a great variety of TLS is available with different range and pulse frequencies (Figure 3).

Figure 3. Basic types of terrestrial 3D laser scanners (TLS) – a brief overview.
A: Faro Focus 3DX130, B: Leica C10, C: Riegl VZ serie,
D: Topcon GLS 1500, E: Surphaser 105HSX, F: Stonex X300.

Handheld (portable) laser scanning

There has recently been an increase in the application of handheld scanners. Their basic advantage is their portability. Scanners that are attached to light portable stands fall in this category as well, even though they are not ‘handheld’ in the true sense of the word (Figure 4). Primarily used in reverse engineering, nowadays they are very often employed in digital documentation of moveable cultural heritage objects (especially objects kept in museums). Although most handheld scanners are based on structured light technology, there is an obvious expansion in the usage of laser portable scanners. Most handheld laser scanners exploit triangulation mechanism (see below), often with the application of calibration targets attached to the object being scanned.

Figure 4. Basic types of portable scanners – a brief overview.
A: Artec Eva, B: Artec Spider, C: David Scanner, D: Sense Scanner, E: Microsoft Kinect,
F: Breuckmann Smart Scanner, G: Faro Scanner Freestyle, H: ZScanner, I: Creaform Go!SCAN.
A-F, I: Structured light scanning (SLS) technology; G,H: Laser technology.

Long- and short-range laser scanning

There is a variety of technologies for digital acquisition of the shape of a 3D object. A well-established classification recognizes two types: contact and non-contact. Non-contact solutions can be further divided into two main categories, active and passive. Based on the principle of technology, in combination with the scale and ranging, the categories described below can be established.

There are two different types of scanners that are commonly used in long-range 3D laser scanning: Phase-Shift (PS) and Time-of-Flight (TOF). The TOF method works by sending a laser pulse of light and then measuring the amount of time it takes to travel from the scanner to the object and back, allowing the scanner to calculate the distance (Armesto-González et al. 2010). An essential part of TOF measurement is the detection method for determining the range and the time of flight. The detector will generate a time-tagged trigger pulse depending on the implemented criterion. Some detection methods take characteristic points of the path of the pulse as the decisive factor (Vosselman, Maas 2010, p. 5). The speed of light is precisely known, so if the information on the time it takes the laser to reach the object and reflects back to the sensor is also known, the location of the object can be determined. A fundamental property of the light wave is its propagation velocity. In a given medium, light waves travel with a constant but finite velocity. The measurement itself is represented by time delays (referred to as the ‘time-of-flight’) created by light travelling in a medium from the source to the reflective target surface, and back to the source (Vosselman, Maas 2010, p. 3). The advantage of this technology is the significant increase in the speed of the data capture – currently up to several million points per second. TOF is typically used for exterior civil/survey applications such as topographic surveys of roadways and buildings, since the key benefit of this type of laser scanning technology is its capability of capturing data from a greater distance (from several hundred up to several thousand metres), while maintaining the accuracy in the order of centimetres or smaller units (Pieraccini et al. 2001; Yastikli 2007; San José et al. 2011).

PS scanners work by sending out a continuous laser beam with a modulated signal embedded in the laser. The scanner compares the phase of the signal at the source with the phase of the laser light once it has travelled to the object and reflected back to the scanner; the change of phase of the laser light is measured and this allows the scanner to calculate the distances (Armesto-González et al. 2010; San José et al. 2011). In comparison to TOF scanners, PS scanners have a lower operational range (80 metres, with some systems reaching up to 120 metres), but can capture more points per second with a higher precision. Generally, PS scanner operates similarly to TOF scanner. The main difference is that PS scanner calculates the time of flight by measuring the difference in the phase of the laser as it returns to the scanner (Bhurtha, Held 2007; Armesto-González et al., 2010). Phase-based scanners are typically used in industrial applications such as plants and refineries, or interior architectural spaces.

While mid- and long-range laser scanners are usually based on TOF technology, systems designed for measuring distances smaller than 5 metres often use the triangulation principle. Triangulation systems typically have an operating range from 0.5 metres to few metres and can collect data with the micron-level accuracy. Short range scanners are used to scan individual small or middle-sized objects, inscriptions and details of architectural features. All short-range scanners are, in fact, portable/handheld devices (Remondino 2011).

The principle of triangulation is based on the laser or light (in the case of structured light scanning) being emitted and returned to a specific location on a CCD array of an inboard camera (Bohler 2006). Most triangulation systems come with a set of lenses that alter the field of view of the system. Most triangulation systems also include an internal RGB capture option, which means that, for accurate colour capture during scanning, a special lighting setup must be used (Pieraccini et al. 2001). Laser triangulation scanners use either a laser line or a single laser point to scan across an object. The sensor picks up the laser light that is reflected off the object and, using trigonometric triangulation, the system calculates the distance from the object to the scanner. The distance between the laser/light source and the sensor is known, as well as the angle between the laser and the sensor. The process of defining these values is called ‘calibration of the device’. The scattered light from that surface is collected from a vantage point distinct from the projected light beam. This light is focused onto a position-sensitive detector. The knowledge of both the projection and the collection angles relative to the baseline determines the dimensions of the triangle and hence the coordinate of a point on the surface (Vosselman, Maas 2010; Feng et al. 2001).

Workflow notes

Laser scanning is usually carried out by experts, and the customer in most cases gets the final product. On the other hand, it is always desirable for the technologist to cooperate on site with a cultural heritage expert (or an archaeologist) in order to achieve satisfactory results and, especially, not to omit important parts of documented structures (e.g. critical details) which require higher level of accuracy. This applies especially to TLSs, given that, in terms of the price, handheld scanners are more accessible to a broader public and are affordable to cultural heritage institutions.

DATA COLLECTION AND PROCESSING[5]

The basic requirement for carrying out a project involving TLS documentation is a proper reconnaissance of the site/structure that is the object of scanning. During this step, basic information on the terrain configuration (flat land, hilly terrain, open land, trees with extensive canopy, etc.), as well as the characteristics of the structure (building material, height, type of roof, the level of occlusion, etc.) is collected. The scanning strategy should be based on the information acquired through reconnaissance. The core part of the strategy is the proper plan of scan positions – the so-called 'stations'. Planning of the stations distribution must accommodate the demand for the total scan coverage, with as few digital shadows as possible. Some parts of the site documented may not be accessible to the scanner device (roofs, upper parts of high buildings, etc.). In such cases, additional technology (like image-based modelling procedure), with the help of unmanned aerial vehicle or a pole, should be involved. It is always good to include in the scanning procedure sketching of the stations positions on a plan, which then helps in orientation in the subsequent scan registration. In this sense, it is advisable to give names to particular scans according to the applied system, which would indicate their position.[6]

It is necessary for the scanning procedure to set the scanning accuracy, which is mostly defined as per distance. The level of accuracy is dependent upon the scale of the project and the commissioning arrangement. In the case of architectural structures, scanning accuracy should not go below 6 mm per 15 metres. For subsequent registration[7] of particular scans, (ground) control points ((G)CP) have to be captured. These points are marked on the spot and scanned with the help of a special prism. Then, they are measured with the total station. The level of the measurement accuracy should not exceed 6-7 mm; otherwise the final registration of the scans can cause 'ghosting' effect.[8]

Most laser scanners are equipped with an inbuilt camera which can generate composite photos. The final scans derive RGB information from the photos taken at the same position where the scan was created. Unfortunately, most scanner cameras have unsatisfactory sensors, with small resolution, so the final RGB values are of very poor quality.[9] In addition, processing softwares have limited possibilities for managing certain RAW files. Therefore, it often happens that some parts of the scanned structure have underexposed or overexposed RGB values, which are then very difficult to fix during the final texturing (Figure 5). To achieve a good texture, it is necessary to use proper external camera for photo documentation, which can be afterwards used in texturing the final mesh in external software.[10] Moreover, the possibility of merging laser scan and image based scan data has recently emerged with the application of Capturing Reality's RealityCapture software.[11]

The basic output of laser scanning is a point cloud of a specific density and resolution. The majority of native scanner processing software can export the point cloud either in

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[5] This chapter is primarily concerned with TLS since the data acquisition by portable laser scanners is very similar to that of structured light scanners.

[6] If scanning a building, it is advised to name the scans according to the rooms, floors, wings, etc.

[7] In scanning technology, the term 'register' is used in place of a more general expression 'align'.

[8] Especially in case of flat surfaces (e.g. walls), inaccuracy can generate double structures.

[9] This does not involve Riegl scanners, which use standard external DSLR cameras attached to the scanner.

[10] The majority of external point cloud processing software packages enable texturing of the mesh using external photos (e.g. Geomagic Design X, Geomagic Wrap, PolyWorks, MeshLab). The procedure involves manual selection of common reference points on the photo and on the 3D model.

[11] Capturing Reality RC requires laser scan data format PTX as an input, in order to read the scanning positions and align them with the image data.

the scanner's native file (e.g. FLS – Faro native format, PTZ and PTG – Leica native format, etc.) or in the generally interchangeable file formats such as PTS, PTX or ASCII.[12] Both file types store point clouds with the topographic information (X, Y and Z coordinates of each point) and intensity and colour information (R, G and B values of each point). Furthermore, the PTX file format contains information on the position of particular scanning stations.[13] This format contains the above-mentioned data as well, but, due to its structure, it is very difficult to work with when it contains a large amount of data.[14]

The first step of scan-data processing is scan registration, i.e. the alignment of all scans of particular scanning stations into one common point cloud. Scan registration can be carried out either in the scanner's native processing software using the measured GCP, which is the preferable option, or in an external software (commercial or open-source). External software is predominantly used for the registration of common points in point cloud pairs which are defined manually, or it applies semi-automatic aligning process based on fusing common parts of the point clouds (e.g. Autodesk ReCap). In the latter case, sufficient overlapping between registered point clouds is required.

After all the scans have been registered, the final, aligned point cloud is generated and this is then subject to further processing. Depending upon the needs of the project, it can be subsampled. The final step is mesh generation. Most native scanner software packages are not very good in doing this. Nowadays there are many meshing algorithms included in a number of software packages, both commercial and open-source. The main drawback of the majority of software is the limitation in size of the point cloud and the final mesh they are able to handle.[15] Currently, the most common algorithm used for meshing a point cloud is the so-called 'Poisson reconstruction' (for details see Khazdan, Hoppe 2013) which tends to build watertight mesh by interpolating missing data and giving a smooth result, while maintaining the surface details. Another option is the basic triangulation with software-specific variations, which delivers the exact surface structure.

Software	License	Point cloud registration	Meshing algorithm
Geomagic Design X	commercial	manual, semi-automatic	Native, based upon triangulation
Geomagic Wrap	commercial	manual, semi-automatic	Native, based upon triangulation
PolyWorks	commercial	manual, semi-automatic	Native, based upon triangulation
3D Reshaper	commercial	manual, semi-automatic	native
Thinkbox Sequoia	commercial	manual, semi-automatic	native
Capturing Reality RC	commercial	manual, semi-automatic	native
Autodesk ReCap	commercial	manual, semi-automatic	no
CloudCompare	open-source	manual, semi-automatic	Poisson
MeshLab	open-source	manual	Poisson[23]
VRMesh	commercial	manual, semi-automatic	Native

Table 1. Overview of the most commonly used point cloud editing and meshing software.[17]

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[12] In case of airborne LiDAR data, LAS or LAZ file format is the most common.

[13] It is also called 'structured scan file format' because it enables special forms of visualisation and lighting. PTX files are usually much larger than PTS files.

[14] Notably, opening an ASCII file containing more than 10 million points can, in some cases, be an issue.

[15] Most software opackages have problems with meshes containing more than 80 million triangles.

[16] Beside Poisson reconstruction, MeshLab also offers other meshing algorithms, e.g. Ball pivoting and VCG, but Poisson surface reconstruction is the most suitable option in the majority of cases.

[17] In open-source software, there can be constraints in the readability of particular RAW files; also, some of the mentioned editing tools may be missing.

STRUCTURED LIGHT SCANNING (SLS)

Structured light scanners use trigonometric triangulation as the basic technological means, but instead of looking at laser light, these systems project a series of linear light patterns onto an object using either an LCD projector or another stable light source. Light patterns are collected, or, rather, recorded with a camera. Then, by examining the edges of each line in the pattern, the software calculates the distance from the scanner to the object's surface. Essentially, the camera sees the edge of the projected pattern and calculates the distance and size of the scanned object. In order to obtain the structure of the scanned object, the light source also needs to contain all basic colours, i.e. red, green and blue (RGB), and emit them towards the object being scanned. The reason for this is the working principle of RGB cameras as data capturing devices. The SLS technology is very popular, especially in light portable (handheld) scanners.

There are two components of which SLS typically consists: a light source and a camera. The light source transmits patterns of the surface scanned. The patterns consisting of parallel stripes are most commonly used, although many other variants of projection are as well in use. Displacement of the stripes allows for an exact retrieval of 3D coordinates of details on the object's surface (Fofi et al. 2004). The light patterns are recorded with RGB camera. Then, by examining the edges of each line in the pattern, the software calculates the distance from the scanner to the object's surface (see above).

Generally, there are two types of these scanners. The first type has the ability to change the distances between the camera and the light source, which leads to changes in the angle between the camera and the light source. In this kind of system, the calibration panel is used to determine the position and the angle of the light source and the camera. The second type has a fixed light source and a camera. In this case, the distance between them is constant and does not change through the process. Thus, in this method, it is necessary to set a good distance between the object and the scanning pair (camera and light source). In some cases, video projector can be used as a light source.[18] Principally, the stripes generated by display projectors have small discontinuities due to pixel boundaries; however, these can practically be ignored as they are ironed out by slight defocusing. A typical measuring assemblage consists of one stripe projector and at least one camera. Placing two cameras on opposite sides of the projector can also be useful (Fofi et al. 2004).

There has recently been a significant increase in the use of structured light portable/handheld scanners, especially due to their increasingly accessible price. A number of projects have demonstrated their possible applications, as well as the limitations of their use in archaeology and in cultural heritage management in general (Buchón-Moragues et al. 2016; McPherron et al. 2009). On the other hand, traditional laser scanning approach usually provides higher accuracy rate.

The following comparison is based upon personal end-user experience and not upon any scientific analysis.

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[18] David SLS scanner uses LCD video projector for emitting light patterns.

<table>
<tr><th colspan="2">Laser Scanner Method</th></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>• Can be used in virtually any indoor lighting condition
• Can be used to scan parts of any material and colour
• Provides excellent depth resolution for measuring details of features, compound curves, cracks, etc.
• Little noise in point cloud
• Highly reliable accuracy</td><td>• ‘Speckle-effect’ may sometimes pose limitations to the resolution and accuracy
• Higher prices</td></tr>
<tr><th colspan="2">Structured Light Scanner Method</th></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>• Fast when measuring objects with many low-curvature surfaces
• Good lateral resolution along the two axes
• Eye-safe
• Customer-friendly price</td><td>• Sensitive to ambient light. Best used in a dark room
• Cannot be used to scan shiny surfaces
• ‘Occlusion’ effects require taking additional images
• Slow when measuring objects with many intricate details
• In terms of accuracy, usually less reliable than laser technology</td></tr>
</table>

Table 2. Comparison of light and laser technologies.

As mentioned above, SLS is almost invariably used in handheld or portable scanners (Figure 4). The structured light-emitting source is either represented by an ‘independent’ device, mostly a projector that is in some way connected to the capturing device, or is directly integrated into a single device (e.g. Artec scanners: Eva and Spider). Just like in the case of TLS, SLS’s main task as regards data capturing is to avoid digital shadows and cover the whole object scanned. This can be a delicate issue, as SLS usually requires a certain distance from the item being documented. To this end, it may be impossible to capture occluded parts of the object’s surface with only one SLS scanner type.[19] SLS has limitations in view of the scanning distance, which is reliable up to one metre at the most; so it is obvious that it is suitable primarily for digital documentation of small- and medium-sized objects. Therefore, this technology is used mainly in museum collection documentation. Some SLS devices cannot operate under direct sunlight, which can cause problems in open-air work. In such cases, portable tents or shelters are required to block the direct sunshine.

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[19] In the case of Artec scanners, type Eva operates within longer distances from the object, while the Spider type works within a closer range and is capable of capturing fine occluded details.

SLS technology usually functiones by gathering data with its native software. Hence scanning, in this case, necessitates the use of a notebook or tablet, which enables real-time preview of the scanning process. Some native scanning software may require specific notebook/tablet configuration especially concerning the CPU (processor), GPU (graphic card) and RAM. Unlike TLS, most SLS software carry out complete processing and post-processing of the data acquired from the point clouds registration, meshing and texturing, so there is no need to use external software. Besides native software, most present-day portable SLS scanners can use Artec Studio for previewing the scanning process as well as data processing. Artec Studio was designed as native software for Artec scanners and provides workflow for the entire procedure – from the registration of particular scans to mesh processing and editing.

Figure 5. Manor house at Žehra, Hodkovce, Slovakia. Point cloud with RGB values showing exposure inconsistency due to poorly exposed composite photos taken by the native scanner camera (Leica C10).