# 3D Scanning for Cultural Heritage Conservation - A quick guide

Over recent years 3D scanning has become part of a coherent and non-contact approach to the documentation of cultural heritage and its long term preservation. High-resolution 3D recordings of sites, monuments and artifacts allow us to monitor, study, disseminate and understand our shared cultural history – it is essential that the vast archives of 3D and colour data are securely archived. An integral component of this work is to record surfaces and forms at the highest possible resolutions and archive them in raw formats, so the data can continue to be re-processed as technology advances. In some cases the data will need to be re-materialised as a physical object - and this is where a great deal of misunderstanding exists.

Digital used to be associated with virtual but now the ability to re-materialise data as physical three dimensional objects is demanding new explorations into the types of information the data contains. The levels of damage and destruction of heritage sites caused by mass tourism, wars, iconoclastic acts, the ravages of time, commercial imperatives, imperfect restoration and natural disasters has led to a re-evaluation of the importance of high resolution facsimiles. This approach is helping visitors understand the complexity involved in preservation and is leading to a renegotiation of the relationship between the original and the authentic. Exact facsimiles are being made possible through advances in 3D recording, composite photography, an assortment of multi-spectral imaging techniques, image processing and output technologies.

A number of different 3D scanning methods exist, each with their own advantages and limitations. The challenge is to identify the right system for the right application. No one system can do everything. The diverse method of capturing 3D data evidences this. Time of flight, triangulation, photogrammetry and a host of different approaches are redefining the relationship between image and form. The 3D data can be on a vast scale, recording the topography of a landscape from great distances or it can be close range and accurate enough to document the surface of a carving; marks that are not easily visible to the human eye can be visualized for epigraphic study or condition monitoring.

While some systems can obtain colour data as well as 3D information, currently no 3D scanner is able to record colour to the standard required for the production of an exact replica. All 3D recording is based on metrology; the science of making measurements. Outlined below are the main techniques and scanners used at Factum Arte and the reasons they are used in the way they are.

# Types of 3D Scanning

**Long-Medium Range 3D Scanners (LiDAR)**: Used to record the general shape of large objects and surfaces with the aim of getting accurate metrological information.

**What we use it for:** Topography and the recording of buildings: We have used the FARO Focus$^{3D}$ X 330 in conjunction with ScanLAB Projects, London to record the façade of San Petronio in Bologna, *The Last Supper* by Leonardo da Vinci and the whole of the refectory at Santa Maria Delle Grazie, Milan. It would have been ideal to record the walls of the Citadel in Aleppo, Syria before they were seriously damaged by a tunnel bomb.

**We don't use it for:** Recording the subtle detail of surfaces that is required to make an accurate facsimile or for epigraphic study.

Visualization of Bologna's Piazza Maggiore and the facade of the Basilica recorded with FARO Focus$^{3D}$ X 330 ©The Basilica of San Petronio

Long-medium range scanners use time-of-flight or laser-pulse based systems where a laser light is bounced off the target at a distance. A laser range finder calculates the distance to a surface by timing the round trip of a pulse of light using the known value for the speed of light.

In cultural heritage documentation, long-medium range scanners are normally used in combination with close-range 3D scanners to generate models with both global metrological accuracy and high resolution surface detail.

**Close Range 3D Scanners** (more than 8cm and less them 1m working distance): Used to record the shape and surface of objects in great detail. Close recording distance is usually associated with higher resolution.

**What we use it for:** Scanning the surface of paintings and reliefs like the Hereford Mappa Mundi and Goya's *Black Paintings*. Recording shape and surface of sculptures and complex forms like the tomb of Tutankhamun, the hieroglyphs on Tutankhamun's sarcophagus, the decay on the surface of the sculptures on the façade of San Petronio or in the crumbling Romanesque cloisters in Tudela.

The output can be both for study using screen-based applications or to be re-materialised for a range of purposes including tactile objects for the blind and partially sighted, facsimile production and exhibition display.

**What we don't use it for:** To record large structures for screen viewing. Close range scanning is slower than long-medium range scanning or photogrammetry.

A re-materialisation of the Hereford Mappa Mundi, recorded with the Lucida 3D scanner

A render of a relief from the Basilica of San Petronio in Bologna, recorded with NUB3D SIDIO structured light scanner

Close-range scanners use either laser or a structured light system. Triangulation based 3D laser scanners use a laser light and one or two cameras to record a subject. Through trigonometry, the distance of the object to the scanner can be calculated thus creating a precise map of the surface. Structured light scanners also use triangulation but use projected patterns of light instead of a laser. The camera(s) records the projected patterns and calculates the distance of every point in the field of view.

Close-range 3D scanning in its many variations is essential for recording ‘at risk’ heritage. To meaningfully document the past it is essential to be able to document not just the general shape but also the subtle details of the surface of the object. This is why Factum Arte has been using several different close-range 3D scanning systems.

**Photogrammetry:** Photogrammetry is the science of making measurements from photographs.

**What we use it for:** The quick recording of vulnerable and inaccessible sites. Photogrammetry is the ideal way to obtain 3D information in situations where it is not possible to use 3D scanners (inaccessible locations, conflict zones), or when high-speed recording is required (scanning people, living organisms, liquids in movement). It is ideal for the recording of translucent surfaces like alabaster and marble. Due to the composite nature of the image capture, colour and form can be extracted from the data. Factum Arte has applied this technology to record the Stelae at Nahr el Kalb in Lebanon and is currently perfecting both the technique and the software in order to record the Sarcophagus of Seti I in Sir John Soane’s Museum. We have recently completed the construction of a 9 camera system capable of recording objects up to about 50 x 50 x 50 cm in about 4 seconds.

**What we don’t use it for:** The highest resolution recording of surface for facsimile production and featureless, reflective and dark surfaces. It is possible that with software improvements photogrammetry will soon become the dominant method for recording at risk cultural heritage in 3D and colour.

Left: 3D rendering of the Stelae to Esarhaddon 688 - 699 BC in Nahr El Kalb, Lebanon; recorded and processed with photogrammetry. Right: Detail of the Stelae after being routed in high-density polyurethane in Factum Arte

Photogrammetry has been used since the birth of modern photography in fields such as topographical mapping, architecture and archeology. Factum Arte's work and research is focused on close range photogrammetry as a means to record the form and texture of surfaces and objects. Recent developments are based on advances in computer vision technologies and SfM (Structure from Motion) software.

The data can be recorded with commercially available cameras that capture multiple shots of the entire surface of an object. Close-range photography can result in high-resolution data. Basic processing is required in the field to ensure that no areas have been missed. Post processing is time consuming. Factum Arte's agenda at present is to record as many sites as possible at the highest practical resolution.

**A note about resolution**

There is a great deal of misunderstanding about accuracy and resolution. The way we are using the term resolution refers to the level of detail a 3D file holds. We evaluate the resolution not just by a theoretical or mathematical description of the sensor of the scanner but by the correspondence between the scanned data and the original surface. Close range scanners have greater correspondence to the surface of the object than long-range scanners.

The main variables that affect the resolution are the lenses, the sensors, the area that is being scanned and the software algorithms that process the data. Somewhere in this mix of elements is the sweet-spot that will result in data that passes the 'mimesis test' - If it looks like a sweet that has been sucked it has failed - if in direct comparison with the original it looks the same it has succeeded.

A routed sample from the façade of the Basilica of San Petronio in Bologna illustrating the difference in resolution and accuracy between close-range and long-medium range scanning – in this case the NUB3D SIDIO (left) and the Faro Focus$^{3D}$ X330 (right).

Scanners Used in Factum Arte

## FARO Focus$^{3D}$ X 330

The FARO Focus$^{3D}$X 330 laser scanner (a LiDAR scanner) records a 360° environment of wherever it is placed. In Factum Arte we use the FARO, in conjunction with ScanLAB Project, as a complimentary tool to create an accurate digital canvas on to which we can place higher resolution surface scans.

The FARO Focus$^{3D}$X 330 scanning system: used at an average resolution of 0.6mm scanning in 360° from 14 different positions when scanning the Basilica of San Petronio, Bologna

William Trossell from ScanLab Projects using a LiDAR scanner to record Leonardo da Vinci's *Last Supper*, oil, tempera, fresco, 1495-98 (Santa Maria delle Grazie, Milan)

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| Technique: Time-of-flight / laser pulse-based 3D scanner |
| Recording distance: Long-medium range (0.6 m-330 m) |
| Resolution: Dependent on the level of detail required and proximity to object; 1 million to 750 million points per scan |
| Correspondence to surface of the target: Relatively low |
| Recording time: Dependent on resolution and quality settings; 30 seconds – 2 hours per scan |
| Processing time: Depends on the data and desired output but on average very long |
| File formats: Native scan format is .FLS; exports in point cloud format |
| Equipment: Terrestrial LiDAR scanner, survey tripod and tribarch, camera and panomaker, reference geometry/targets |
| Environmental Conditions: Overcast, even lighting, avoid direct sunlight and rain |
| Operation: 1 person. Skill level: Moderate; survey and geomatic based background required |
| Processing: Extensive and requires both skill and artistry. Skill level: Expert; geomatic and digital visualisation experience necessary |
| Applications: Documentations of indoor and outdoor environments i.e. monuments, buildings, archeological sites, cathedrals (exterior and interior) etc. |
| Advantages<br>• Small, lightweight instrument<br>• Long range, non-invasive capture of large features and forms<br>• A 70 megapixel camera records colour and overlays photographs for a more detailed looking scan<br>• Simple, intuitive scanner interface<br>• No computer required for capture<br>• Built in replaceable battery |
| Limitations<br>• Does not capture high resolution data of the texture and surface of an object (limiting its use for the production of facsimiles or in-depth study)<br>• Divergence of resolution at range<br>• Processing requires an expert skill level<br>• Glossy, reflective and translucent surfaces are difficult to scan |
| What can you do with the data?: 3D walkthroughs of environments or buildings, screen based imaging, 3D printing, survey archeological sites, etc. |

**Lucida 3D Scanner**

Lucida is a 3D laser scanner designed and developed by the artist Manuel Franquelo and custom built by Factum Arte. It obtains high resolution recordings of the surfaces of works of art and low relief objects. This system has been developed to obtain 3D information of surface and texture, not colour.

Left: The Lucida 3D Scanner Right: Lucida 3D scanner recording Bellini's *Assassination of Saint Peter Martyr* (99.7 x 165.1 cm) in *The National Gallery*, London

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| Technique: Triangulation based 3D laser scanner |
| Recording distance: Close range (8-10 cm) |
| Resolution: 100 microns (10,000 points per cm²) |
| Correspondence to surface of the target: Very high |
| Recording Time: 4 hours per m² |
| Processing time: 4-6 hours per m² (dependent on computer processing power and experience of the operator) |
| File formats: AVI (raw video), RIS, 32 bit TIFF, 8 bit TIFF (shaded render) |
| Equipment: Lightweight CNC frame and controller, scanning head (pocket sized), laptop |
| Environmental conditions: No vibrations, low ambient light levels |
| Operation: 1 person. Skill level: Basic |
| Processing: 1 person. Skill level: Basic |
| Maximum recording size: Dependent on the structural frame |
| Applications: Walls, frescoes, rock art, paintings (canvas, board etc.), maps, fabrics (tapestries), manuscripts, coins, wax seals etc. |

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| Advantages<br>• Can record a variety of surfaces that are normally problematic for other 3D scanners (i.e. shiny, highly contrasted, gold or metallic surfaces)<br>• Saves data as unprocessed raw video<br>• Automatically outputs 3D data rendered as 2D shaded images<br>• Data can be combined with other sets of data (e.g. UV, infrared, colour etc.)<br>• Portable, easy to assemble and operate; relatively inexpensive<br>• Mains or battery operated<br>• The software for scanning, editing and stitching has been designed to be open source |
| Limitations<br>• Sensitive to vibrations<br>• Sensitive to strong directional light<br>• Limited depth of field (2.5 cm); for higher reliefs, several scans at various distances are needed<br>• Slow scanning speed<br>• Cannot record transparent or translucent surfaces |
| What can you do with the data?: Re-materialisation of the relief (CNC milling) for the creation of exact facsimiles; screen based imaging in combination with other layers of data (colour, etc.) |

**Kreon Zephyr 50 3D Scanner**

Kreon Zephyr 50 3D scanner is a handheld scanner secured to a robotic arm that can be used to scan a variety of structures and objects. The early handheld scanning systems (like this Kreon) required a 6 or 7 axis arm but due to the amount of research and development resulting from the games industry systems are now available that are completely hand-held.


Left: The Kreon Zephyr 50 3D scanner head mounted on a robot Right: Gabriel Scarpa using the Kreon system (Cimcore Stringer arm pictured) to scan the head of a winged genie $9^{th}$ C BC relief from Harvard's Arthur M. Sackler Museum

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| Technique: Triangulation based 3D laser scanner |
| Recording distance: Close range; the sensor has a depth of field of 50 mm, the arm we worked with had around a 2 m reach |
| Resolution: Dependent on the scanning speed; maximum resolution 50 microns (0.05 mm) |
| Correspondence to surface of the target: High |
| Recording/Processing Time: 30,000 pts/s |
| File formats: Polygonia Software exports every kind of point cloud and mesh formats |
| Equipment: Zephyr 50 Scanner, Cimcore Stringer II axis 6 arm, laptop, tripod |
| Environmental Conditions: Can be used in diverse environments |
| Operation: 1 person. Skill level: Moderate |
| Processing: 1 person. Skill level: Moderate |
| Maximum recording size: The reach of the arm - more or less an area of 2 $m^2$ |

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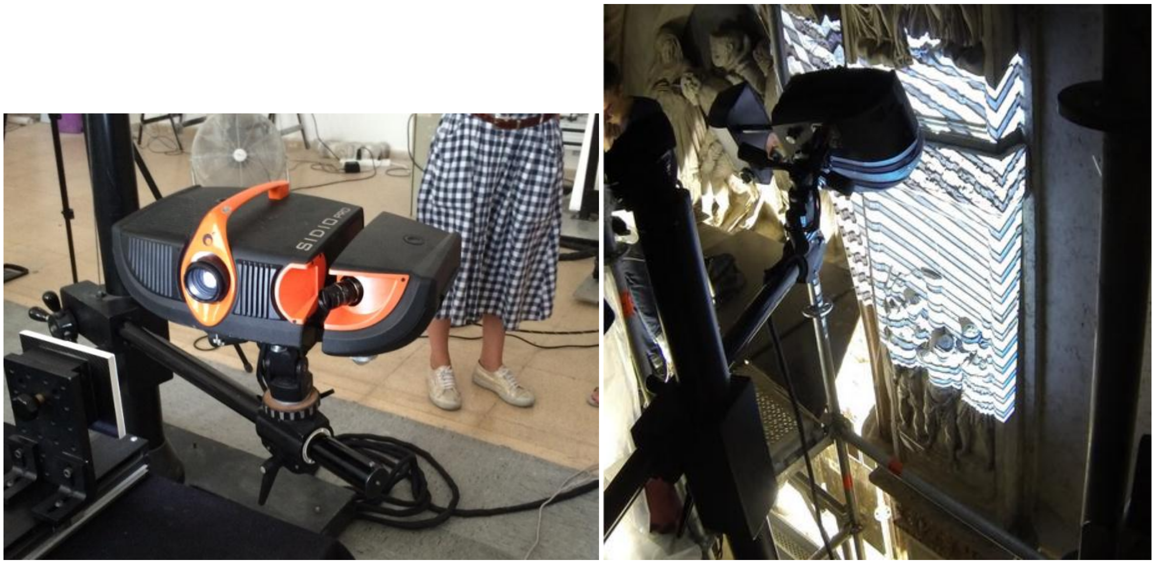
| Applications: Quality control in automotive, aeronautic and construction industries, reverse engineering, records sculptures, facades, objects etc. |
| Advantages<br>• Portable, light, easy to operate<br>• Can record hard to reach places<br>• Records in diverse conditions<br>• Records complicated undercuts |
| Limitations<br>• Slow scanning process; object has to be rescanned to provide sufficient high resolution data<br>• Scan area is limited by the length of the Cimcore arm<br>• Very sensitive to vibrations; tripod requires a very heavy base to provide stability<br>• At the time of use (2006/7) the software restricted the amount of data that could be scanned at one time; there was also no clear visualisation of the area scanned<br>• Needs mains power |
| What can you do with the data?: Screen based applications, 3D printing, reverse engineer objects, prototyping |

**Nub 3D SIDIO Scanner**

Factum Arte has worked with Nub3D, a company based in Barcelona who developed the SIDIO scanner, since 2006. The SIDIO is one of our most useful systems as it captures the full geometry of objects with high surface detail and outputs the data in clean point cloud formats.



Left: The Nub 3D SIDIO scanner during calibration Right: The SIDIO scanning one of the pilasters of the left door on the façade of the Basilica of San Petronio, Bologna

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| Technique: Structured light scanner |
| Recording distance: Close range; 30 cm / 60 cm / 1 m (each corresponds to a different area) |
| Resolution: It can output a resolution of 75, 130 or 250 microns |
| Correspondence to surface of the target: Very high |
| Recording Time: Dependent on a number of variables such as shutter speed, characteristics of the object etc., but overall quite quick (a few seconds per scan) |
| Processing Time: The processing time depends on the complexity of the object scanned |
| File formats: Point cloud; the native format is .TRI - It has to be exported as .PIF to be inputted into an post processing software like Polyworks |
| Equipment: 3 tripods, scanner, 2 external projectors, a powerful desktop computer, calibration rail, calibration plates |
| Environmental Conditions: Dark/low-light environment, no vibrations, mains power |

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| Operation: It is possible with 1 operator but 2 is ideal. Skill level: Moderate |
| Processing: Skill level: Expert |
| Maximum recording size: 50cm² per scan session. |
| Applications: Sculptures, reliefs, rocks, facades etc. - anything that needs to be scanned with a lot of detail and precision |
| Advantages<br>• Automatically pre-aligns on sight with a marker system<br>• Accurate and high quality measurement<br>• Data is a clean and ordered point cloud<br>• Control over the post processing and mesh generation<br>• Small company where the people selling the systems are also designing and building them<br>• It is difficult to damage |
| Limitations<br>• Heavy, a lot of equipment, need space to operate (newer versions have improved on these issues)<br>• Cannot scan anything too dark, translucent, reflective or glossy<br>• Halogen light generates significant heat<br>• Sensitive to vibrations<br>• Needs mains power<br>• Expensive aligning software<br>• Complex calibration system<br>• Only one camera<br>• Expensive |
| What can you do with the data?: Screen based applications, 3D printing, re-materialisation for the production of facsimiles, reverse engineering, high-resolution data allows for in depth study |

**Breuckmann Smart Scan 3D**

The Breuckmann scanner outputs high resolution 3D meshes and is used in Factum Arte for a variety of artistic and conservation projects. The Breuckmann, and similar systems, are used widely because of their accurate yet simple recording and processing methods.

Alex Peck from Factum Arte setting up a 3D scanner in Henry Hudson's studio to scan a maquette

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| Technique: Structured light scanner |
| Recording distance: Around 1 m |
| Resolution: This scanner has two different set ups; the M-410 which records at a resolution of 140 microns at about a 30x30 cm area per shot and the M-810 which records at a resolution of 250 microns and a 60x60 cm area per shot. |
| Correspondence to surface of the target: Very high |
| Recording Time: Dependent on resolution but overall faster than the SIDIO . |
| Processing Time: Relatively faster than the SIDIO scanner; the system is designed to generate 3D meshes easily |
| File formats: 3D mesh in formats such as .OBJ and .STL |
| Equipment: Scanner, tripod, laptop with a powerful GPU and a minimum of 32 GB RAM as the OPTOCAD software works on RAM memory to build meshes, calibration tools |
| Environmental Conditions: Dark/low-light environment, no vibrations, mains power |
| Operation: 1 operator (2 preferred). Skill level: Moderate |

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| Processing: 1 person. Skill level: Moderate |
| Maximum recording size: 1 m² per scan session |
| Applications:  Sculptures, objects, reliefs, rocks, facades etc. |
| Advantages<br>• Lighter, faster and less equipment (when compared to the SIDIO)<br>• Captures colour (resolutions: 0.8 - 2.0 - 8.0 Megapixel)<br>• Waits for vibrations to stop before scanning<br>• No need to use markers for combining scans<br>• Has two cameras and scans by combining the information<br>• Can do a combination of photogrammetry and structured light measurement resulting in a high level of accuracy<br>• Uses an LED light which does not generate heat<br>• The software aligns the scans immediately and offers a preview of the model making the data easy to work with<br>• Processing and mesh output is straightforward for rapid prototyping |
| Limitations<br>• Cannot access the point cloud as the system is designed to output 3D meshes through the OPTOCAD software (it is possible to extract points from the mesh but this is not as accurate as original point cloud data)<br>• Calibration plate is large<br>• Needs a mains power<br>• Expensive |
| What can you do with the data?: Screen based applications, rapid prototyping, re-materialisation |

**Photogrammetry**

Photogrammetry is a way of extracting 3D information from 2D images using feature mapping software and a range of algorithms. In order to make a 3D model a camera takes multiple images with overlap of the surface of the object. The images can then be processed to create a 3D model for various applications.


A canon EOS 5D Mark 2

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| Technique: Photogrammetry |
| Recording distance: Can be long and close range; in Factum Arte we are focusing on close range photogrammetry |
| Resolution: The resolution is dependent on the amount of images, their quality and the level of overlap between them as well as the post processing software. Also dependent on the size of the subject relative to the sensor on the camera. |
| Correspondence to surface of the target: Medium/High – normally there is noise to be processed or cleaned |
| Recording Time: Dependent on the type and size of surface being recorded but generally quick |
| Processing Time: Time consuming; dependent on computer CPU, GPU, RAM memory and experience of the operator |
| File formats: Raw data is converted into JPEG in order to optimize the speed of processing. These can then be aligned and exported as a point cloud or as a 3D mesh in several formats – e.g. OBJ files |

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| Equipment: Photogrammetry can be implemented using any form of image capture technology; for photogrammetry of cultural heritage sites and artefacts the recommended equipment is a standard DLSR camera, a tripod and a laptop (preferred for checking data on site but not imperative) |
| Environmental Conditions: Even, diffused lighting (avoid strong shadows or highlights – flash is effective for close range recording), approximately 80% overlap of photographs from multiple points of view, perpendicular shots to the target surface, detailed features, colour, and texture preferred |
| Operation: 1 person. Skill level: Basic knowledge of photography |
| Processing: 1 person. Skill level: Moderate |
| Maximum recording size: Very large (can be used to record topography) |
| Applications: High and low reliefs, sculptures, monuments, faces, objects, hard to reach places through the use of drones etc. |
| Advantages<br>• Fast recording time<br>• Minimal, portable and affordable equipment<br>• An accessible and adaptable process<br>• Battery operated<br>• Produces raw files<br>• Can record high resolution and accurate colour<br>• Can record translucent surfaces such as alabaster<br>• Can record whilst moving and record moving objects |
| Limitations<br>• Reflective, shiny, featureless and dark surfaces are problematic<br>• Processing time is long (for now)<br>• Accuracy is not as high as structured light scanners<br>• Lack of scale – a reference is needed |
| What can you do with the data?: Screen based applications, archiving for further study and re-materialisation |