

3D LASER SCANNING

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The COSCH Case Studies that have employed this technology: Roman coins, Germolles, Kantharos, Bremen Cog, White Bastion, Romanian cultural heritage

Definition

Traditional surveying uses point measurements of distance and angles. 3D laser scanning does this, thousands or millions of times per second, by emitting a laser beam onto surfaces and measuring the back-scattered energy. Distance is computed from either time delay or phase-shift measurement. Alternatively, for smaller objects, close-range technologies use triangulation of a sensor and a projected pattern, for example, laser line. Therefore, the surfaces can be represented as a collection of measured points in space; as a result a digital point cloud of the surroundings is created without physically touching the surface. These non-contact optical recording technologies are therefore well suited to heritage applications as they do not disturb historic surfaces. Laser scanning is used at different scales, from small objects less than 10 cm in diameter through to heritage buildings and landscapes.

Description

All 3D laser scanners emit opto-electronic signals; the returned signals are measured. These sensors are often used in combination with a camera to include surface colour measurement. The advantage is the remote—that is, non-contact—recording of surfaces at a high speed with known accuracy. Measured surface data are digitally stored and displayed as a cloud of 3D coordinate points.

The 3D laser scanner may be regarded as the next generation of total station (see separate section), with the ability to record millions of coordinate points rather than hundreds.

Two Different Principles of Recording

Medium or Small Objects – Triangulation Laser Scanning

For small tabletop to medium-sized objects (between ca. 15 cm and 600 cm) a scanhead with a triangulation system (see examples 1 and 2) is used. For the triangulation, a laser beam is projected as a line, and its reflection is measured as distance profile by a camera array. The triangle is formed between a laser line projection, an offset optical sensor with a known baseline to the laser emitter, and object surface, and a known angle for the emitted laser line. The projection of a laser line is produced by widening a single laser beam using a cylindrical lens so that it forms a light curtain on the object's surface. The laser line can also be guided over the object by a deflection mirror. The projected laser line is deformed as a function of the distance to the object. The system measures the two-dimensional projection of the laser line on an object, using an optical sensor matrix to calculate a 2D profile. The resulting data is a scan-line-ordered 3D point cloud. The quality of the data depends on the various factors including object's surface and can be adapted by varying laser brightness and using software filtering parameters according to the object's properties. Densities of point clouds typically go down to a point spacing of 0.1 mm with an accuracy of 0.02 mm (20 microns) (VDI/VDE 2617-6.2, 2007).

Line-based laser triangulation sensors need to obtain a location for the automatic alignment of the laser lines in the lateral direction of movement. This can be achieved in multiple ways: optical tracking by a CMM (Coordinate Measurement Machine), mechanical tracking through an arm-based CMM, a moving reflection mirror, or one or more translation stages as well as a self-locating scanhead through targets on the surface of the object. A handheld scanhead guided around the object has the advantage of intuitive operation, as if the user were virtually painting a line over the object's surface from all sides. The operator guides the laser line over the surface, slowly and at a consistent distance and can often walk freely around the object.

Buildings, Landscapes, and Archaeological Sites

Terrestrial laser scanners (TLS) measure distances with known angles to a surface of an object at high speed, using a laser beam, in order to produce 3D coordinates. 3D laser scanners are standard surveying tools, and are used in heritage documentation to record larger objects, building interiors and exteriors, such as archaeological excavation.

A scanhead is typically placed on a tripod, or on the floor, in different positions around the object or space to be recorded. Discrete points are recorded all around this position by a mirror spinning vertically simultaneously with a motor rotat-

ing horizontally, with a rate of ca. 1 million points per second. Today's sensors feature an inbuilt CPU and a touchscreen for easy programming of the job, often a one-touch solution, which increasingly makes a connection to a laptop or battery unnecessary, thus providing a mobile solution for on-site use.

Time of Flight (TOF) or Phase Shift are two methodologies used. The points are measured directly in a metric scale. Like other survey equipment, a laser scanner on a tribrach can be set up over survey control points on the ground. Furthermore, geometrical targets (such as spheres or turn-targets with constant centroid from different viewpoints) are placed around the scene to help align scans at different positions (i.e., the registration of different scans into one common coordinate system). Additional measurements of an independent control network (e.g., known ground control points) measured with a total station, or additional movable targets should be included. If this is not possible, a point-cloud to point-cloud alignment can also be performed. The minimum distance to the object changes by 3D scanner model, but typical values are 1.5 m minimum standoff and 80 m–120 m reach. The sampling density can be as small as a 1 mm × 1 mm grid at a defined distance.

As well as highly accurate 3D data, the laser scanner captures a scene in colour through an inbuilt or added, calibrated camera. The set of coordinate points collected is known as a point cloud. Point cloud data are compatible with many of the CAD programs used in architecture and design. The resulting point cloud can then be used to export 2D floorplans or sections, or to digitally visualize, measure, reconstruct, and interpret the measured data set. Ongoing research explores how 3D imagery from heritage buildings can be translated into information-rich elements by parametric modelling in Building Information Modelling (BIM) systems for building management. Increasingly, research is directed towards Heritage BIM (HBIM, see example 3).

Sources

- Andrews, D., Bedford, J., Bryan, P., eds. 2015. *Metric Survey Specifications for Cultural Heritage*. 3rd ed. Swindon: Historic England. www.historicengland.org.uk/images-books/publications/metric-survey-specifications-cultural-heritage.
- Bryan, P. 2003. *An Addendum to the Metric Survey Specifications for English Heritage. Addendum 1: Terrestrial Laser Scanning User's Guide*. York: English Heritage.
- Luhmann, T., Robson, S., Kyle, S., Boehm, J. 2013. *Close-Range Photogrammetry and 3D Imaging*. 2nd ed. Berlin: De Gruyter, Section. 3.7.1.1.
- Stylianidis, E., Georgopoulos, A., Remondino, F. 2016. "Basics of Image-Based Modelling Techniques in Cultural Heritage 3D Recording." In Stylianidis, E., Remondino, F., eds. *3D Recording, Documentation and Management of Cultural Heritage*, 253–304. Dunbeath: Whittles Publishing.

Tommasi, C., Achille, C., Fassi, F. 2016. "From Point Cloud to BIM: A Modelling Challenge in the Cultural Heritage Field." *Proc. 23rd ISPRS Congress*, Prague, 429–36. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLI-B5. ISPRS.

VDI/VDE. 2007. *VDI/VDE 2617-6.2. Accuracy of Coordinate Measuring Machines with Optical Probing. Part 2: Code of Practice for the Application of DIN EN ISO 10360 to Coordinate Measuring Machines with Optical Distance Sensors*. Berlin: Association of German Engineers. Section 3.2.1.

Significant Applications

Example 1: The Digital Michelangelo Project, 1990s

The Digital Michelangelo Project at Stanford University, USA, involved recording marble statues with 3D triangulation laser scanning. It was the first 3D big data project in the 1990s and therefore ground-breaking for the 3D digitization of cultural heritage. It integrated technical solutions for 3D imaging and dissemination of the results to researchers worldwide through a dedicated website. Mark Levoy, Roberto Scopigno, and other researchers recorded Michelangelo's *David* in Florence in great detail in the late 1990s with a triangulation laser scanner (Levoy 1992). Significant technical knowledge was gained from the scanning of marble as a translucent surface (Godin et al. 2001) and the administration and visualization of large 3D data sets (Levoy et al. 2000). Information valuable for restoration was obtained from the 3D data set of the statue. A 3D data processing strategy and visualization tool for scientific investigation by cultural heritage professionals was developed (Scopigno et al. 2003). Following on from the first imaging project a new data set was recorded with structured light scanning after the restoration of the *David* statue when there were concerns about fine cracks on the surface in 2010. The research on the marble statue and its structural and surface integrity continues to this day.

Sources

Godin, G., Beraldin, J.-A., Rioux, M., Levoy, M., Cournoyer, L. 2001. "An Assessment of Laser Range Measurement of Marble Surfaces." *Proc. Conf. on Optical 3D Measurement Techniques*, Vienna, 49–56. NRC 44210. NRC-CNRC.

Levoy, M. 1992. "The Digital Michelangelo Project." Stanford University. graphics.stanford.edu/projects/mich/.

Levoy, M., Pulli, K., Curless, B., et al. 2000. "The Digital Michelangelo Project: 3D Scanning of Large Statues." *Proc. 27th Conf. on Computer Graphics and Inter-*

active Techniques, ACM Siggraph '00, New Orleans, 131–44. New York: Addison-Wesley. doi:10.1145/344779.344849.

Scopigno, R., Cignoni, P., Callieri, M., Ganovelli, F., Impoco, G., Pingi, P., Ponchio, F. 2003. "Using Optically Scanned 3D Data in the Restoration of Michelangelo's David." *Proc. SPIE Conf. on Optical Metrology for Arts and Multimedia*, Munich, 44–53. SPIE 5146. doi:10.1117/12.499921.

Example 2: The James Watt Virtual Bust, 2010s

This project involved the 3D triangulation laser scanning for non-contact documentation and visualization in 3D of a museum artefact (fig. 12.1). It followed a request from the curator of Mechanical Engineering at the Science Museum, London. It considered the opportunities for 3D imaging and printing in museums and the development of best practice to match the available technology to the needs of users of 3D digital and printed artefacts. This could provide a significant precedent for creating exhibitions and digital documentation for museum holdings.

Non-contact 3D imaging methods and 3D printing were used to produce a physical replica of the original "negative" plaster-cast form, dating from around 1807, which was found in the workshop of the engineer James Watt. It was paramount for the conservation of the original to use a non-contact method so as not to disturb the material and surface inside the mould. The form was complex, composed of four main pieces containing a total of twenty-nine separate sub-pieces. 3D colour laser scanning was used to record the plaster cast with a sampling grid of 0.1 mm. The digital 3D models of the components of the cast form were aligned and the surface normal directions were inverted to create a positive surface model. The result was a first image of the cast and was immediately recognized by the curator as a previously unseen portrait



Figure 12.1. Virtual Reality display and 3D printed replica from 3D scan of a negative cast form. © Mona Hess, 2016.

of James Watt. Further processing followed the curator's decision that the model should show the manufacturing process of the casting and that the joint lines of the single cast form should remain visible and elevated. In a subsequent step the full resolution 10.5 million points was transferred into a high-resolution polygon mesh of 1.5 million polygons for 3D printing as a closed 3D surface without holes (i.e., watertight). A cutting plane was introduced to form a base and bore hole for mounting the bust. This project demonstrated the full production cycle from an original negative plaster cast to the final product in the form of a physical exhibition replica, including the 3D data acquisition to produce a high-resolution 3D virtual model, which can be regarded as the digital equivalent of a conventional plaster cast mould. The replica has been accessioned and exhibited in "James Watt and Our World" and is also available as a Virtual Reality (VR) app.

Sources

- 3DIMPact. Project – James Watt Bust, VR Android application. <https://play.google.com/store/apps/details?id=com.ucl.threedimpact.Watt&hl=en>.
- Hess, M. 2016. "James Watt: A VR Encounter with the Engineer." In Papadimitriou, I., Prescott, A., Rogers, J., eds. *Engineering the Future*, 98–101. London: Uniform Communications.
- Hess, M., Robson, S. 2013. "Re-engineering Watt: A Case Study and Best Practice Recommendations for 3D Colour Laser Scans and 3D Printing in Museum Artefact Documentation." *Proc. Lasers in the Conservation of Artworks IX*, London, 154–62. London: Archetype. <https://iris.ucl.ac.uk/iris/publication/407387/1>.

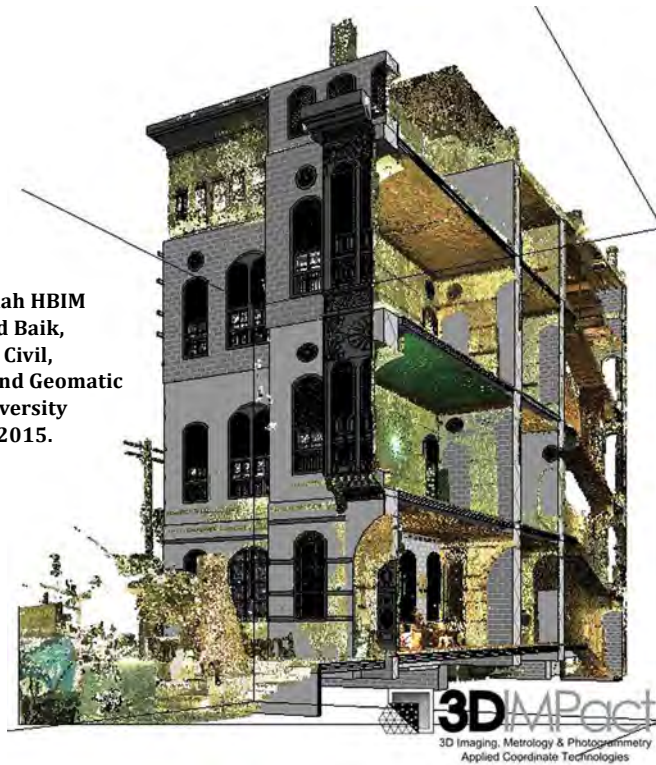
Example 3: Jeddah Historical Building Information Modelling (JHBIM) for the Documentation of Historical Architectural and Monuments

(with kind contribution from Ahmad Baik, 3DIMPact Group, CEGE, University College London)

This project outlines a new approach for the integration of 3D Building Information Modelling (BIM) and the 3D Geographic Information System (GIS) to provide semantically rich models, and to gain the benefits from both systems to help document and analyse cultural heritage sites. Conclusions for dealing with big data in heritage documentation have also been drawn.

Jeddah is one of most important cities in the Kingdom of Saudi Arabia with numerous historic buildings over 300 years old. The major issue that faces Jeddah today is how the government can preserve and save the buildings from the risk of collapse and erosion by natural and human factors, and disasters such as fires. The municipality of Old Jeddah City decided to preserve and develop this area. The geospatial technologies applied were a combination of TLS, remote sensing, Global Position System (GPS), and architectural photogrammetry. These data

Figure 12.2. Jeddah HBIM project. © Ahmad Baik, 3DIMPact group, Civil, Environmental and Geomatic Engineering, University College London, 2015.



sources were used as input to the Jeddah Historical Building Information Modeling (JHBIM) for analysis.

The resulting data (fig. 12.2) provide a shared knowledge resource for the physical and functional characteristics of the historical building facilities in old Jeddah, and will enable decision making about the maintenance of historical structures. Furthermore, 3D models from JHBIM can enable remote reviewing of the interior and the exterior with better understanding than 2D plans and section drawings. The results will be of relevance to a wide variety of disciplines ranging from engineering, architectural and urban studies to geospatial science.

Source

Baik, A., Yaagoubi, R., Boehm, J. 2015. "Integration of Jeddah Historical BIM and 3D GIS for Documentation and Restoration of Historical Monuments." *Proc. 25th International CIPA Symposium*, Taipei, 29–34. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XL-5/W7. ISPRS.

Literature

- Barber, D., Mills, J. 2011. *3D Laser Scanning for Heritage: Advice and Guidance to Users on Laser Scanning in Archaeology and Architecture*. 2nd ed. Swindon: Historic England. https://content.historicengland.org.uk/images-books/publications/3d-laser-scanning-heritage2/3D_Laser_Scanning_final_low-res.pdf/.
- Luhmann, T., Robson, S., Kyle, S., Boehm, J. 2013. *Close-Range Photogrammetry and 3D Imaging*. 2nd ed. Berlin: De Gruyter. Section 3.7.1. On Laser-based systems.