3D-Laser-Sensors and their Applications in Archaeology and Modeling of Historic Buildings

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Abstract: *RIEGL 3D-laser sensors provide the measurement of 3D-information of arbitrary surfaces with high speed and high accuracy in the mm range covering a measuring range of 1 m up to 1000 m and a very wide field-of-view up to 180 x 360 deg. Based on measuring the time-of-flight of near-infra-red pulses and on opto-mechanical scanning this technique provides dense and accurate point clouds describing the surface of the objects or the topography scanned. Additional information on the target's reflectivity and color allows straightforward texturing of models generated from the point clouds. The measurement technique is well suited for documentation, monitoring and recording in archaeology. The scanners provide high-resolution 3D data acquisition of architecture, historic buildings and monuments as well as the topography of the site down to the digital elevation model of the surface of a single archaeological deposit for the recording of a stratigraphic excavation. The collected data can be used for the generation of a highly detailed virtual model of the archaeological site or monument. This paper describes the latest generation of sensors available from RIEGL LMS GmbH and presents archaeological applications at Persepolis, Ephesos, Schwarzenbach and Markgrafneusiedl.*

Keywords: *3D data acquisition, 3D range image sensor, 3D images, texturing, virtual reality*

Introduction

Accurate and high-resolution recording in 3D space is of high importance for many archaeological tasks, in the field as well as for the documentation of finds. More traditional techniques for 3D data acquisition either restrict the size of the scanned objects or impose demands on the stability and structure of the surface. Although laser-based triangulation and fringe-projection techniques in combination with rotational and translational tables offer high data rate and accurate measurement for the documentation of find objects, the method is applicable only to small objects and is applicable only at low ambient light levels. Automatic reconstruction of depth information from two or more photographs taken from different positions again requires a structured surface and/or special lightning conditions. Topographic surveys or the digital documentation of stratigraphic excavations using total stations, GPS devices or photogrammetrical methods can be a laborious task.

Terrestrial 3D imaging laser scanning forms a method to acquire a large number of precise data points in 3D space representing the surface of the objects under investigation. These scanners are an effective tool for the collection of data to create a digital elevation model of the topography of a site as well as of the surface of a single archaeological deposit. Laser scanning is a method that is applicable to document historic buildings or standing archaeological features as walls, columns, monumental statues as well as caves, abris, megaliths or carved rock formations. The acquired data can be used for documentation purposes only but the further processing provides the possibility for virtual reality modeling for public presentation, restoration planning or virtual reconstructions.

In the following we will describe the latest commercially available[1], compact and robust 3D imaging sensors *RIEGL* LMS-Z360 and *RIEGL* LMS-Z420. They are capable of acquiring 3D images even in harsh archaeological field situations.

3D Imaging Sensors

The laser scanner measures, in principle, the distance to a target point and also the respective vertical and horizontal angles. Unlike a total station the laser does not need to be aimed at a distinct target, but 'scans' over a regular pattern of angles in the sight of view of the instrument. Besides target distance, the relative intensity of the returned echo signal as well as the true color of the target point can be recorded, which establishes some kind of link to photogrammetry. The primary data of a 'scan' is mainly a so-called 'point-cloud' in the sensor's local coordinate system. In general it will be necessary to obtain multiple 'scans' from different positions to overcome the problem of occlusions that will be present in any scan from a single point of view. In order to obtain a quite complete representation of the surface by a point cloud, in general numerous scans have to be merged into a common coordinate system. This process also termed “registration” is generally based on scanning tie point objects, which are visible in several scans, but may also be carried out by photogrammetric methods that are based on the intensity and/or color images of the scans. An alternative method is to accurately determine the relative position and orientation of the scanners before data acquisition by classical surveying methods.

The 3D imaging sensors of the *RIEGL* LMS series (see Figure 1 for an LMS-Z360) make use of laser ranging based on the time-of-flight principle and on mechanically deflecting the measurement beam in order to sample the sensor's field-of-view. The implemented time-of-flight measurement technique relies on measuring the time elapsed between emitting a short laser pulse and receiving the echo pulse reflected by the target object. Due to the use of state-of-the-art microelectronics the accuracy of a single measurement is of the order of a few centimeters while achieving a maximum range of some hundred meters at measurement rates up to about 24 kHz. The laser itself is a diode laser or a solid-state laser in the near infrared for the LMS-Z360 and the LMS-Z420, respectively. The main advantage of the solid-state laser is the very narrow measuring beam with a beam divergence of about 0.3 mrad compared to the 2 mrad of the diode laser. A continuously rotating polygon wheel provides a fast line scan with up to 45 lines/sec and a scan range of up to 90 deg.

In order to obtain information in the third dimension such a line-scanning system can either be linearly moved above or beside the object, e.g., by mounting the device onboard of a helicopter, by making use of an additional deflecting device, or by rotating the device.

The 3D imaging sensors of the *RIEGL* LMS-series make use of rotating the line scan mechanism together with the optical front-end of the rangefinder to realize the second scan motion. This combination of a fast line scan and a rather slow frame scan leads to a compact and robust unit with a wide field-of-view of up to 90 x 360 deg. See Table 1 for a summary of the main features of the systems *RIEGL* LMS-Z360 and *RIEGL* LMS-Z420.

[1] www.riegl.com

Figure 1: 3D Imaging Sensor *RIEGL* LMS-Z360 mounted on a tripod.

Data acquired with the system are organized in a nearly regular polar grid, i.e., the step width in horizontal and azimuth angle is constant during acquisition of a frame. Step size can be set via commands ranging from 0.01 deg to 0.4 deg. For the diode laser system, at a step size of below 0.18 deg the laser footprints overlap on the target's surface. In order to achieve optimum foot print size in the near range (up to 10 m) also with the diode laser based system, the measuring beam can be focused by software commands. The two scan mechanisms are not synchronized and both scan mechanisms are continuously scanning. Thus, line scans are not strictly vertical. The frame scan mechanism allows fixed positioning and the *RIEGL* LMS instruments can also be used as a 2D line-scanning device.

The spatial resolution of the system is limited by the range accuracy in radial direction and by the beam divergence in the tangential direction or cross range. For the diode laser system ranging accuracy is 12 mm, and the laser footprint size increases with range according to the beam divergence of 3 mrad at a rate of 30 cm per 100 m. In case of more than one target within the laser beam the rangefinder provides a weighted average of the range as long as the targets are separated less than about 2 m. The weighting factor is given by the reflectivity of the targets. For targets with a range difference in excess of 2 m the system can be configured to provide either the range to the first or to the last target. For the solid-state laser system, the foot print diameter increases with 3 cm per 100 m.

Both sensors provide beside the geometric information, additionally the intensity of the echo signal for every measurement. Intensity information can be used to generate an active image of the scene at the laser wavelength, which has proved to be very useful for object identification based on the acquired data. Intensity information also allows automatic extraction of retro-reflecting reference targets as they show up clearly in the intensity image. The *RIEGL* LMS-Z360 sensor provides also color information by means of a 1-pixel RGB sensor co-axially aligned with the laser beam. Therefore, the color data can be applied directly to the geometric data and allow thus texturing a model in a straightforward way. Color information is provided as 3 x 16-bit information to cover a wide dynamic range.

The LMS-Z420 can be optionally equipped with a high-resolution digital camera, which is firmly mounted to the rotating part of the instrument. To cover the full field-of-view of the laser instrument, the camera takes a number of shots at defined frame angle positions. Once the camera is calibrated every image acquired can be registered in the scanner's coordinate system in a straightforward way. Thus every point (measurement) of the point cloud can be attributed a color from the images taken, or the images can be mapped as a texture onto the models generated from the point cloud.

Table 1: Key specifications of *RIEGL* LMS-Z360 and *RIEGL* LMS-Z420

	LMS-Z360	**LMS-Z420**
Rangefinder performance		
Measuring range [1)2]	2m up to 200m	2m up to 250m in class 1 mode 2 m up to 1000 m in class 3R mode
Range measurement accuracy [3)]	12 mm	10 mm up to 250 m 20 mm up to 1000 m
Laser	0.9µm/Class 1 (eye safe)/3 mrad beam div	1.06µm/Class 1 (eye safe) or Class 3R/0.3 mrad beam div
Measurement rate	8000 - 24000 points/s	3000 - 9000 points/s
Scanner performance		
Line scan range	Up to 90 deg	Up to 80 deg
Minimum line scan step width	0.01 deg	0.01 deg
Angular resolution of line scan	0.002 deg	0.002 deg
Frame scan range	Up to 360 deg	Up to 360 deg
Minimum line scan step width	0.01 deg	0.01 deg
Angular resolution of line scan	0.0025 deg	0.0025 deg
Physical data		
Main dimensions (LxØ)	490 mm x 210 mm	463 mm x 210 mm
Weight	approx. 13 kg	approx. 14.5 kg
Power supply	12 – 28 V DC, 4 A @15 V DC	12 – 28 V DC, 4 A @15 V DC
Temperature range	Operation: -10°C to +50°C, Storage: -20°C to +60°C	Operation: 0°C to +40°C, Storage: -10°C to +50°C

1) First, Last, or First & Last target alternatively selectable
2) typical values for average conditions. In bright sunlight, the operational range is considerably shorter than under an overcast sky. At dawn or at night the range is even higher.
3) Standard deviation, plus distance depending error ≤± 20 ppm

During data acquisition, the companion software 3D-RiSCAN visualizes acquired data on-line as color-encoded range image, intensity image, and true color image. Neglecting the angle information and arranging the pixels according to the scan pattern form the images. For the purpose of an improved object recognition the color-encoded range image may be intensity modulated with the intensity information. Figure 2 shows an example of images provided by 3D-RiSCAN based on a single scan. Scan range is 40 deg x 32 deg, 520 000 measurements, color encoding for range image (left image) 14 m to 44 m.

The native file format to store 3D data equals the data stream of the *RIEGL* LMS-series instrument, provided either at a parallel port or a TCP/IP interface. Exporting the data in standard formats enables easy data transfer to other 3D data processing packages. Currently implemented export filters allow storage of single 3D image data or 3D image sequence with optional high resolution time stamping of data including PC time in the native binary 3DD format, export of data as point cloud or as triangulated mesh of surface in VRML, VTK

(*Visualization Tool Kit* format[2]), STL, OBJ, and DXF. Furthermore, 3D information can be exported directly interfacing to *PolyWorks*[3] in PIF format including color or intensity information, or as plain text (ASCII) with a user-definable data string format and data string content in ASCII format. The native binary file format can be read by commercially available software packages, e.g., *Orpheus*[4], *Reconstructor*[5], *QTSculptor*[6]. Integration of the sensor into an existing software environment is supported by RiSCANLIB, a scanner library for decoding the binary data and for setting parameters of the sensor designed for Microsoft Windows platforms.

Figure 2: Example of the on-line visualization by 3D-RiSCAN from the survey at Persepolis, Iran.

Archaeological Applications

Persepolis, the Gate of All Nations, Iran

The historical city of Persepolis [7] is located 55 km north of Shiraz in southwest Iran. Persepolis was the capital of the Achaemenid Empire, founded by Darius I in 518 BC. It was built on an immense half- artificial, half-natural terrace, where the king of kings created an impressive palace complex inspired by Mesopotamian models. The importance and quality of the monumental ruins make it a unique archaeological site that is registered World Heritage.

In February 2002 primary test measurements were carried out together with the local company *TEKNO Co*. and specialists from the Cultural Heritage Organisation of Iran *CHOI*. The list of requirements defined by the *CHOI* included the creation of digital maps of different types (topography, monuments, etc), a 3D visualization of the site to be used for virtual reality models and detailed documentation of carvings and reliefs on the walls and facades. To meet the last requirement mentioned, that falls beyond the laser scanners capabilities, a combination of close range photogrammetry and 3D laser scanning was recommended.

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[2] Willi Schroeder et al., The Visualisation Tool Kit, 2nd edition, Prentice Hall PTR, 1998. www.kitware.com
[3] Innovmetric Software Inc., Quebec, Canada. www.innovmetric.com
[4] Institute of Photogrammetry and Remote Sensing, Vienna Univ. of Technology, Austria.
[5] 3D-Veritas, www.3dveritas.com
[6] Polygon Technology GmbH, www.polygon-technology.de
[7] http://www.livius.org/pen-pg/persepolis/persepolis.html

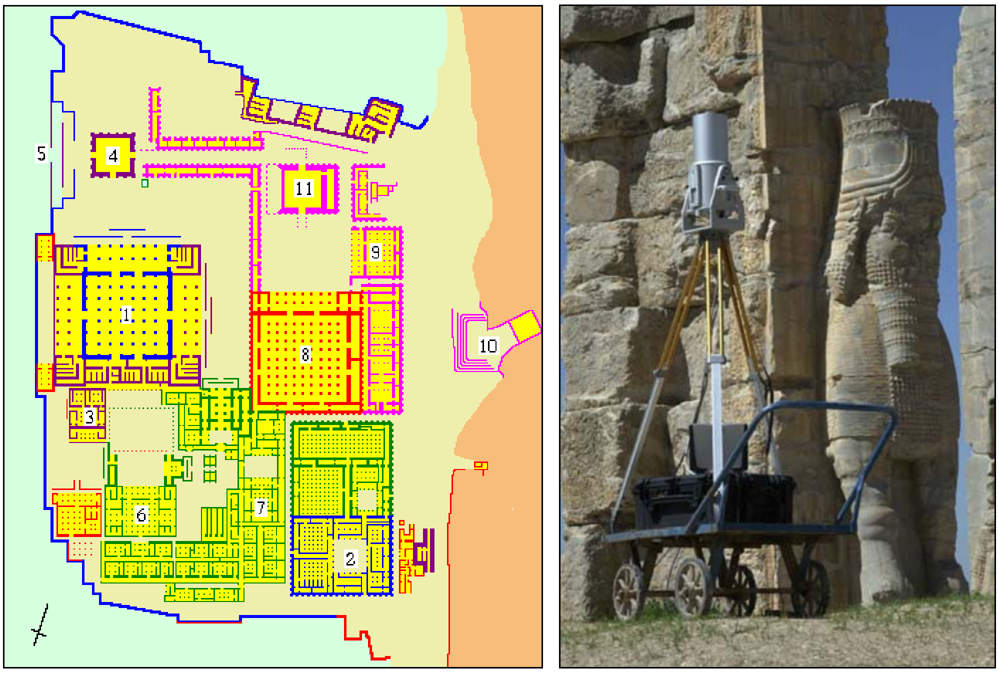


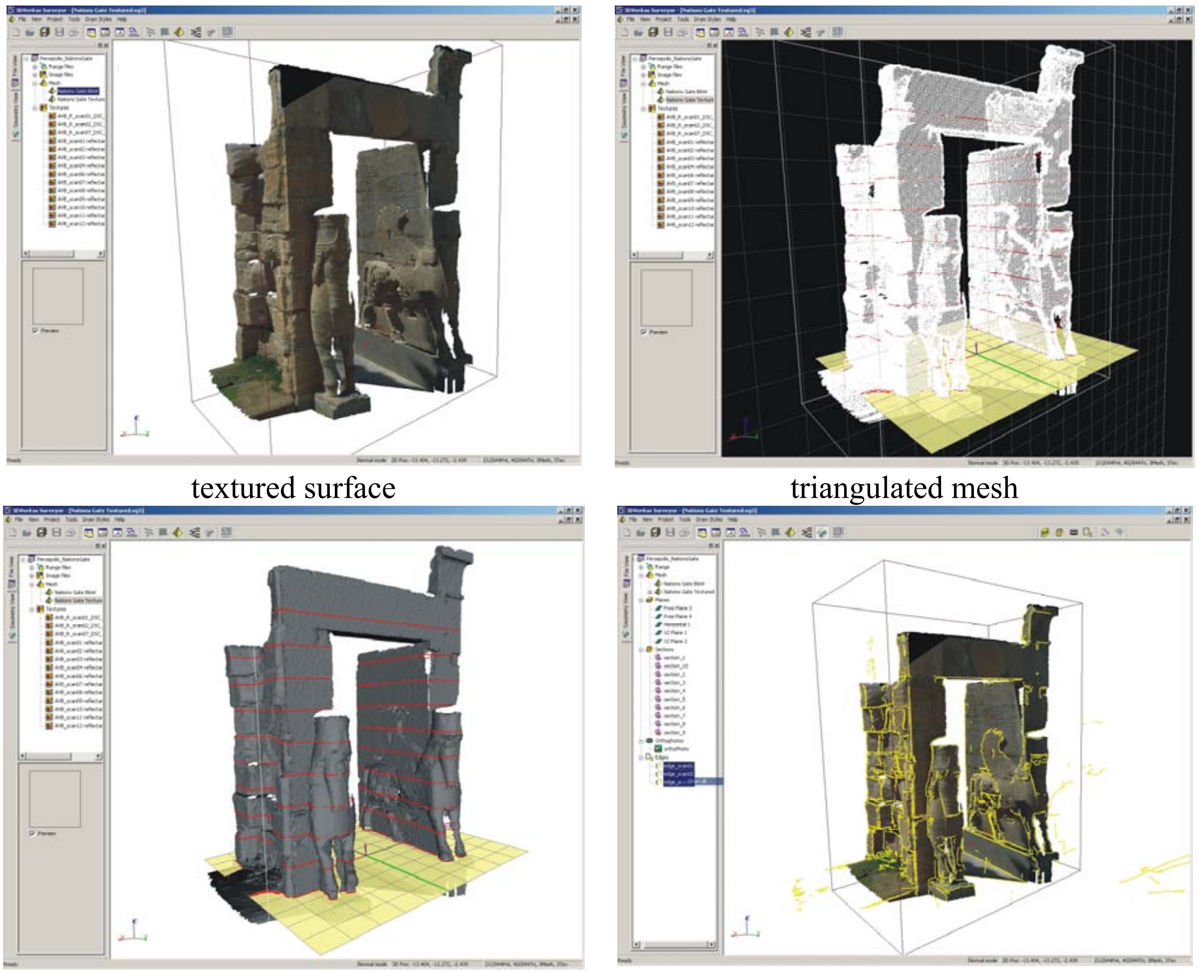
Figure 3: Left: Site map of Persepolis. 4 : The Gate of All Nations (from [1]) . Right: *RIEGL* LMS-Z360 in front of the Gate of All Nations in 2002.

Figure 4: 'Gate of All Nations', left: point cloud of 9 true color scans, created semi-automatically whilst scanning right: orthophoto of merged scans and photographs

For testing the capabilities of the instrumentation three areas were selected: The Hall of 100 Columns (Figure 3, 8), the Gate of All Nations (Figure 3, 4) and the Ardeshir gravesite. The areas were scanned using a *RIEGL* LMS-Z360 in a total time of 21.5 h, collecting nearly 3 GB of raw data.

As an example of the test survey we present the Gate of All Nations (also known as Xerxes' gate) that was scanned in an area of 30 x 30 m. It is situated north of the Apadana (the audience hall, Figure 3, 1). It is guarded by a pair of large bulls in the west and lamasu's in the east. A lamasu is a bull with the head of a bearded man (Figure 3, right). Xerxes, who built this structure, named it The Gate of All Nations for all visitors had to pass through it on their way to the Throne Hall to pay homage to the king. The building consisted of one spacious room whose roof was supported by four stone columns with bell-shaped bases. Parallel to the inner walls of this room ran a stone bench, interrupted at the doorways. The exterior walls of the structure, made of thick mud brick, were decorated with numerous niches. Each of the three walls, on the east, west, and south, had a very large stone doorway. Engraved above each of the four colossi is a trilingual inscription attesting to Xerxes having built and completed the gate. The doorway on the south, opening toward the Apadana, is the widest of the three. Pivoting devices found on the inner corners of all the doors indicate that they must have had two-leaved doors, which were probably made of wood and covered with sheets of ornamented metal.

To document the reconstructed remains of this important monument we scanned from 12 positions with two resolutions. At any position a medium angular resolution of 0.12 deg (scan time: 4 min) was selected for the first overall scan (360 x 95 deg) later used for registration. For the second scan a detailed area was selected and scanned with an angular resolution of up to 0.01 deg (scan time: 3-5 min). For registration and merging of the data into one coordinate system we used a series of reflectors positioned around the monument. For the combination of two scans, using a least square fitting procedure, at least four common reflectors have to be visible in both scans. The 3D-RiSCAN software allows the automatic extraction of the reflectors based on their reflectance intensity. The post processing of the data included data filtering, creating a 3D presentation file by merging the selected parts of the single scans.



textured surface — triangulated mesh

surface with cross- sections — edge detection

Figure 5: 'Gate of All Nations', post processed by Reconstructor /3DVeritas.

Markgrafneusiedel, historical building, Austria

The site Markgrafneusiedl is situated 20 km east of Vienna. The restored historical building, a rectangular fortification tower dated to the 12th century, that was later used as a church donated to St. Martin, played an important role in the battle of Deutsch Wagram in 1809, when Napoleon did beat the Habsburg troops[8]. The rounded tower set on top of the rectangular one was built in the middle of the 19th century, when the church became on of the regions largest wind mill.

The restored remains of the building were documented by 3D laser scans from the outside and the inside. From the collected data a fully 3D model of the church can be derived and used as primary documentation for preservation purposes.

Table 2: Scan details

	panoramic scans: field of view: 360° x 90° angular resolution: 0.012 °	detail scans: field of view: adjusted angular resolution: 0.005°
Number of outdoor scans	9	9
Number of indoor scans	5	1
File size of scans	40 MByte / scan	10 - 15 MByte / scan
Scan time	4 minutes per scan	3-5 minutes per scan
Used number of tie points	approx. 20 cylindrical retro reflectors	
Number of operators	1	
Duration of data acquisition	8 hours	


Figure 6: Left: RIEGL LMS-Z360 at work on a 4m high tripod to document the historical building. Right: 3D visualization of the acquired point cloud.

[8] http://www.histoire-empire.org/essling/combats_a_markgrafneusiedl.htm
http://www.histoire-empire.org/essling/newmarkgraf.htm

Figure 7: Front and side view of the colored 3D point cloud.

The prehistoric settlement Schwarzenbach-Burg

The prehistoric site Schwarzenbach-Burg is situated on top of a hill 60 km south of Vienna. The site was already occupied in the late Neolithic period and during the Bronze Age. An area of 15 ha was fortified with a rampart in the 2nd century BC, when the hill became an important regional political and economic center in the sense of an oppidum. The interdisciplinary archaeological research is one of the main projects of the Vienna Institute for Archaeological Science[9] and started in 1992. GIS-based digital recording techniques of stratigraphic excavations were developed there and tested at the excavations since 1998. Together with *RIEGL LMS GmbH* the excavation campaign 2002 could be monitored for two weeks using the *RIEGL* LMS-Z360 and LMSZ210 devices. The scanners were used for a high-resolution 3D recording of the surface of the open 900 m^2 trench, so far done using a total station.

For registration of the scans 11 reflectors were mounted on fixed positions. Right after the digging out of a single deposit, the surface of the trench or parts of it were scanned, using the highest resolution of the specific instrument. The collected and registered point clouds were resampled on a 5 or 10 cm regular grid and converted in the native *ArcView* shape-format.

[9] www.univie.ac.at/vias

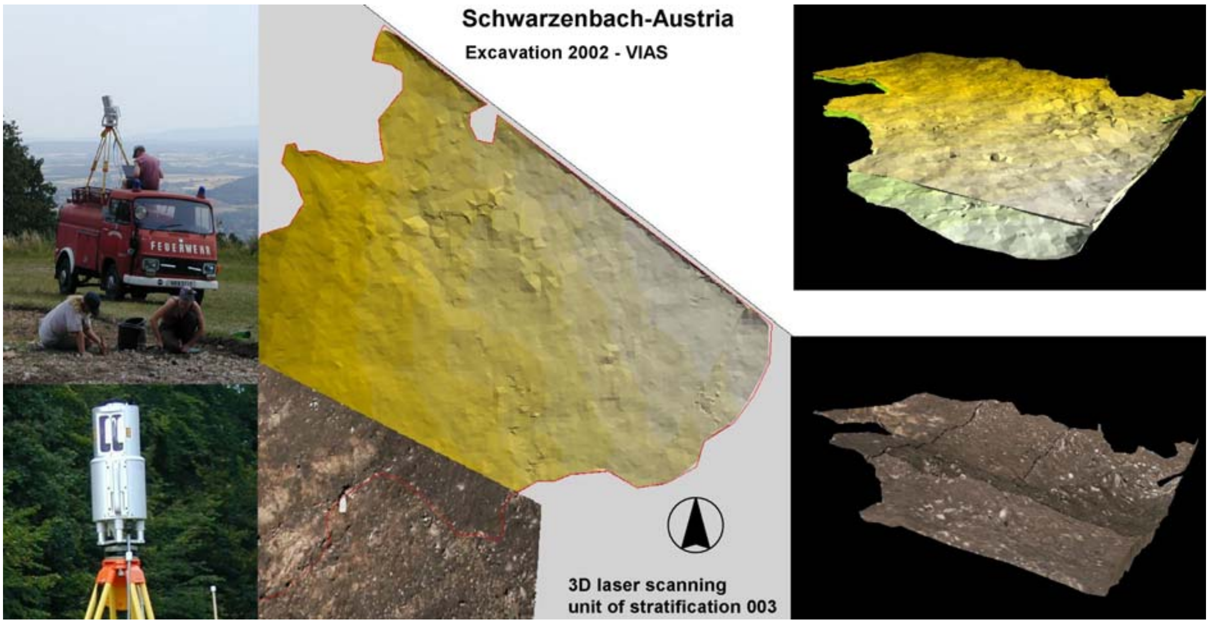


Figure 8: 3D laser scanning for the documentation of single surfaces at the excavation Schwarzenbach. Left: *RIEGL* LMS-Z210 laser scanner in action. Centre: Outbound polygon, rectified photograph and triangulated surface of a single surface. Right, top: 3D visualization of the top and the bottom surface of the deposit 003. Right, bottom: 3D visualization of the top surface with mapped digital orthophoto.

For further data processing we used the function of the GIS *ArcView*[10] and the beta-version of the developed *ArcDig* extension. The single surface of a deposit was clipped from the triangulated topographic scan data using the outbound polygon of the stratification unit, measured with the total station. Rectified digital photographs were mapped on top of the triangulated surface. The digital photos are rectified so far by using control information from at least 4 tie points. The scanner data provides the possibility for the automatic creation of high resolution orthophotos. Using this procedure, the single surfaces of the excavated deposits can be visualized according to the stratigraphic sequence of the trench. The 3D laser scan devices showed a high reliability and efficiency for topographic single surface recording in every day archaeological work. The scanner, as used here, could do the same recording job, done so far by two people, in only 20% of time collecting up to 50 times more data. This would save at a typical 1 month excavation up to 100 man hours. The 3D laser scanner can be seen as a future standard tool for the high-resolution 3D recording of single surfaces on a stratigraphic excavation.

Ephesos, the Celsus Library, Turkey

One of the finest structures in the ancient city of Ephesus, the Celsus Library[11], has recently been restored by Austrian archaeologists[12]. It was built by the Consul Gaius Julius Aquila in 135 AD. as a heroon in honor of his father, Celsus Polemaeanus, the governor of Asia Minor. The facade is highly ornamented on two levels, and there are three main portals. Over the portals were columns and statues arranged in niches. These statues were female figures representing the virtues wisdom, fate and intelligence. Niches on the interior of the building were designed to hold books. The tomb of Celsus was placed in a crypt below the central large

[10] www.esri.com
[11] http://www.ephesusguide.com/celsus.html
http://www.focusmm.com/aceph_26.htm
[12] www.oeai.at

niche. According to the inscription on the architrave of the building, Gaius Julius Aquila died before it was completed, and the construction was carried on by his heirs. He left 25000 denars for the acquisition of books for the library. The library was burned down totally approximately in the 3rd century. The front wall was not destroyed totally. It was restored after the disaster and a small pool was constructed right in front of the building. These restorations were done roughly in the 4th century.

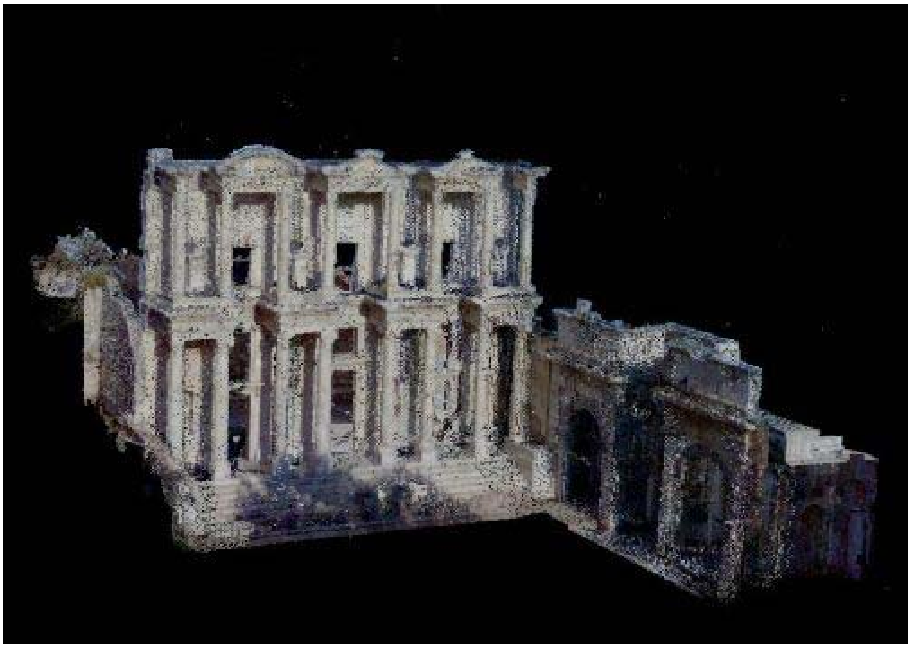


Figure 9: 3D visualization of the main facade of the Celsus library.

In September 2002 the Celsus Library and its surrounding was documented in 3D using a *RIEGL* LMS-210. This sensor has a ranging accuracy of 2.5 cm, the laser footprint diameter is about 40 mm in the near range. The project financed by the Austrian Archaeological Institute was carried out by *VIAS* in cooperation with *RIEGL LMS.* The site is visited by hundreds of tourist every day from sunrise to dawn. As the Celsus library is one of the most prominent monument, it was not possible to keep the tourists out. Therefore it was only possible to scan in the early morning and late in the evening, thus the true color images are of poor quality. The monument was scanned from 16 positions with a scan range of 80 x 333 deg using the highest angular resolution of the instrument (0.072 deg). Registration of the scan data into a common relative coordinate system was done by reflectors spread over the site. The reflectors absolute coordinates were measured using a *LEICA* total station and used for georeferencing of the point cloud. The various filters provided by the 3D-RiSCAN software were used to clip out the scanned persons. The point cloud was later resampled on a regular grid of 5x5x5 cm. This data set will be used for testing software packages under development for the automated reconstruction of compact (parameterized) 3D models from unorganized point clouds. Up to now, this post processing step still needs human interaction.