Rosenburg – Rapid State-of-the-art 3D Documentation and Mapping of a Medieval Castle Using Terrestrial Laser Scanning, Unmanned Laser Scanning and Ground Penetrating Radar

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The detailed 3D documentation of medieval castles in heavily accessible topographic settings or partly hidden behind dense vegetation encounters major challenges to conventional topographic, geodetic or photogrammetric surveying. This paper presents a rapid solution for the detailed documentation of the upstanding architecture and remains hidden in the subsurface by combining “terrestrial laser scanning” (TLS) and “unmanned laser scanning” (ULS) with motorized “ground penetrating radar” (GPR). The large medieval castle Rosenburg, Lower Austria situated on a prominent mountain ridge provided a typical situation for a respective case study to present a state-of-the-art solution for fast and efficient high resolution surveying above and below ground. The used terrestrial laser scanner *RIEGL* VZ-400i[1] is able to perform hundreds of automatically registered scans per day. A *RIEGL* VUX-1UAV[2] laser scanner system mounted on the multi-copter RiCOPTER was applied to measure the roof landscape in minutes and supplement the ground-based data acquisition. A motorized multi-antenna GPR system based on a 16-channel MIRA system from *Malå Geoscience AB*, adapted for efficient data acquisition by the *LBI ArchPro*, provides detailed 3D information on subsurface remains like vaults, cisterns, walls of previous buildings up to the remains of garden layouts. The case study exemplifies the latest developments in data acquisition, processing and the combination of such hybrid 3D data sets including the fast and efficient production of 2D maps and plans for heritage management duties.

Key words:
Terrestrial Laser Scanning, Unmanned Laser Scanning, Ground Penetrating Radar, Data Combination.

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[1] http://www.riegl.com/nc/products/terrestrial-scanning/produktdetail/product/scanner/48/

[2] http://www.riegl.com/products/unmanned-scanning/riegl-vux-1uav/

INTRODUCTION

Many archaeological or historical sites are defined by both, remains preserved above ground and archaeological remains hidden beneath the ground. The demand for a detailed digital 3D documentation of such sites requires appropriate methods, which allow the highest resolution with correspondingly efficient application procedures [Studnicka et al. 2013; Neubauer 2007; Ullrich et al. 2002].

Typically, the two components of such sites are documented in separate processes focusing on the still standing structures on the one hand and the archaeological remains on the other hand.

In most cases, the work is carried out by different specialized teams and the respective specifications of the survey parameters are defined independently from each other. A detailed and comprehensive combined digital documentation often fails because the survey methods used for the digital recording above and below ground have different resolutions, the corresponding 3D data formats are not directly compatible with each other, or a combined visualization of the complex 3D data sets can only be achieved via detours. In most observed cases no requirements are defined beforehand for the necessary subsequent data combination to derive a complete 3D digital model of the respective site. This is one of the reasons why the full potential of the available three-dimensional documentation cannot be exploited. It is also of particular importance, but still often remains unnoticed, that the complex 3D data sets created by the experts are made accessible in a comprehensible way to ensure that they can also be dynamically used by persons responsible for cultural heritage management or development to derive appropriate products from these data for the respective prevailing issues.

THE CASE STUDY ´ROSENBURG´

The present case study ´Rosenburg´ was defined based on a site, which presents different characteristic challenges for such a digital 3D documentation. The 2.5 ha large medieval castle complex of the Rosenburg in Lower Austria (Fig. 1) approx. 90 km northwest of Vienna, is situated on a rocky ridge overlooking the Kamptal valley. The current castle unites elements from various phases of the Middle Ages.

Fig. 1. Aerial view of the Rosenburg from the East

The castle was built in the 12th century in Romanesque style. Its first documented mention dates back to 1175. Of this small castle of the Goczwin of Rosenberg, only the foundation walls keep remain today. In the 15th century, the Rosenburg was extended to a larger Gothic castle under Kaspar von Roggendorf. The chapel and outer walls of this castle are still preserved today. However, between 1593 and 1597 a large part of the Gothic castle was demolished. The present Renaissance chateau with 13 towers was built in its place. Around 1614 the castle also received a 0.5 ha large tournament ground and 46 arcades. The Rosenburg came to the Hoyos-Sprinzenstein family, which still owns it today, through the marriage of Leopold Karl Graf Hoyos (1657-1699) to Maria Regina Gräfin Sprinzenstein in 1681. Between 1859 and 1875 Ernst Karl von Hoyos-Sprinzenstein restored the Rosenburg Castle, which was threatened by decay, according to the depictions of the palace in the *Topographia Windhagiana* of 1673 (Fig. 2), and made it one of the first castles in Austria to be open to the public. The current owners Petra and Markus Hoyos invoked and supported this case study, which was carried out by the Ludwig Boltzmann Institute for Archaeological Science and Virtual Archaeology (www.archpro.lbg.ac.at) in collaboration with Riegl Laser Measurements GmbH (www.riegl.com) between 2018 and 2019.

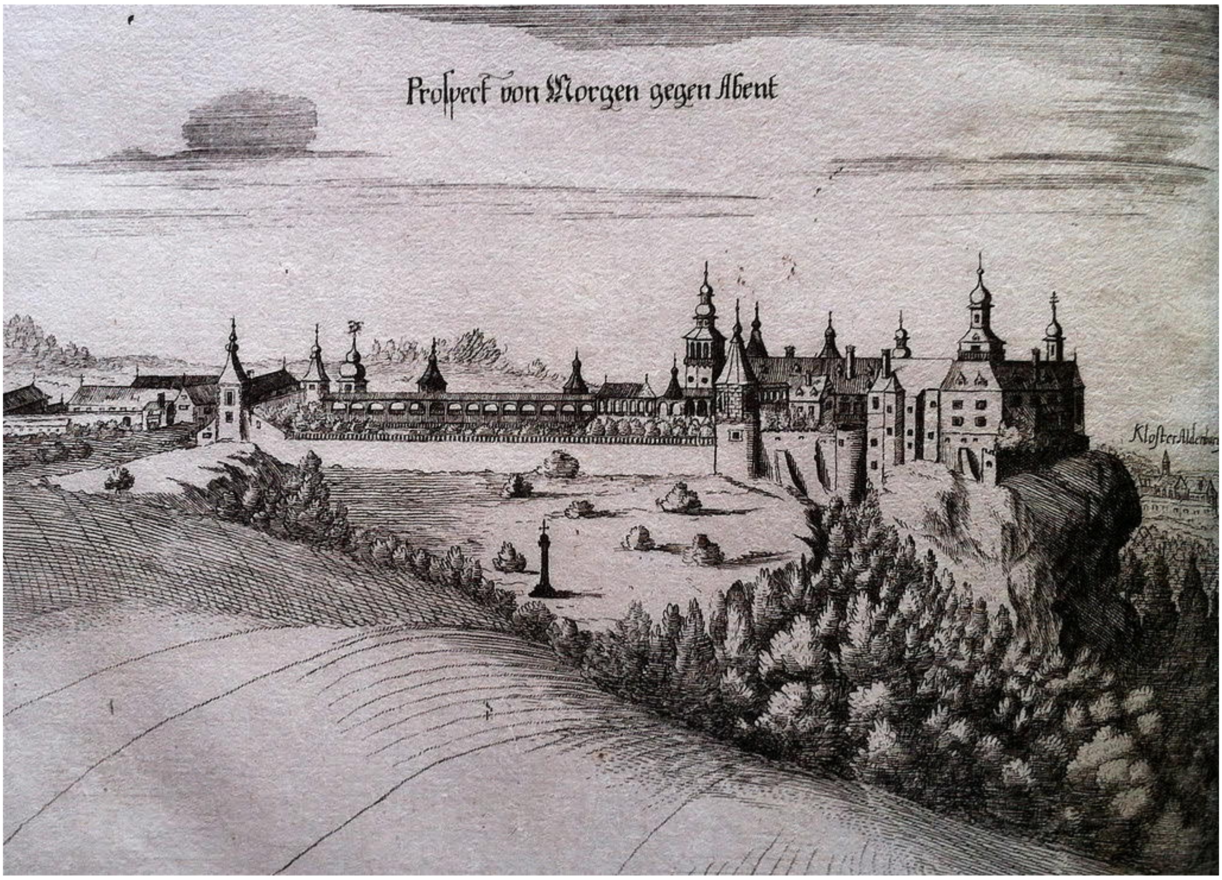


Fig. 2. Rosenburg Castle against the West as depicted in the Topographia Windhagiana, Vienna 1673

The castle complex Rosenburg is not accessible from all directions. The steep rock formations in the direction of the valley are covered with dense forest and the roof landscape is largely invisible from the ground. Larger trees and bushes inside the castle provide further obstructions for the recording process. The wide tournament ground and a comparable large garden terrace facing to the southeast form together an approx. 1 ha large area, accessible to non-invasive geophysical prospection.

The detailed 3D documentation of the standing building structures of such a castle in a heavily accessible topographic setting and partly hidden behind dense vegetation encounters major challenges to conventional topographic, geodetic or photogrammetric surveying. Therefore, an efficient solution for the detailed documentation of the upstanding architecture of the castle and the presumed remains hidden in the subsurface had to be developed.

The objective set for the documentation of the buildings was to obtain a high-resolution point cloud, whereby all trees and bushes were to be removed from the data. In general, two different methods are available for this purpose. On the one hand, a geodetic survey based on terrestrial or airborne laser scanning and on the other hand terrestrial or airborne photogrammetry, for example via image based modeling is applicable. A further objective was to obtain a point cloud already registered/georeferenced in the field, whereby the strategy to be developed for this purpose should be based on a robust workflow.

Due to the various modern disturbances magnetometry could not be applied for the non-invasive prospection of the open areas in the southern part of the castle. “Ground penetrating radar” (GPR) offers the greatest potential for three-dimensional investigation of the subsurface. The choice fell on high-resolution measurements with motorized antenna arrays with medium frequencies and hand-held antennas with low frequencies, resulting in deeper penetration.

The selected approach was based on the combination of state-of-the-art 3D “terrestrial laser scanning” (TLS) and “unmanned laser scanning” (ULS) with motorized high resolution 3D “ground penetrating radar” (GPR). The goal was that all data should finally be visualized and analyzed in a comparable resolution within a single 3D software package. In the following, we would like to explain the technical basics and the methodical steps chosen for the creation of the standardizable solution in more detail. The logistics, work flows and procedures developed for the three combined survey methods are described, which made the efficient and complete documentation of such a complex building possible. Subsequently, the provision of measurement data for the intuitive creation of orthogonal views and sections from the complex 3D data set for facilitating the analyses and further mapping demands will be discussed.

TLS - TERRESTRIAL LASER SCANNING

Data acquisition – logistics, specifications and work flows

For the state-of-the art terrestrial laser scanning, a latest *RIEGL* LMS VZ400i scanner combined with a *Nikon* D-810 (14 mm lens) was selected (Table 1, Fig. 3b). One main objective of the case study was the development of a time efficient and robust scanning work flow ensuring a straight forward automatic registration process and highest accuracy and resolution of the final point cloud.

For the scans the standard scan pattern "Panorama40" with an angular resolution of 0.040° (7 mm @ 10m distance) and five 36 MP photos each was selected. The mean net scanning time per scan position observed is 45 seconds including the shooting time for the 360 degree photographic record. It is necessary to limit the exposure time in order to produce the sharpest possible photos when taking scans and photos simultaneously (depending on the scan pattern and thus the rotational speed of the scanner head). With the scan pattern "Panorama40", this is set to a maximum of 1/200 sec. Since the aperture is fixed at 8 for a large depth of field, the ISO sensitivity of the camera must be readjusted manually or automatically. With these settings, a total duration of less than 80 seconds on average per scan position including the adjustment of the tripod can also be achieved over a longer period of time. The terrestrial scan project consists of 344 individual laser scans collected within one day.

Table 1. Specifications of the terrestrial laser scanning (TLS)

Laser scanner	*RIEGL* VZ-400i
Photo camera	attached Nikon D-810 (14 mm lens)
Field of view of the laser scanner	100° vertical x 360° horizontal
Scan pattern	„Panorama40“
Angular resolution (resolution on the facade)	0.040° (7 mm at 10 m distance)
Measurements / scan	approx. 22.5 millions
Precision	3 mm at 100 m as given in the data sheet
Resolution of a single photograph	36 MP
Time per scan position (inclusive movement)	approx. 80 s

The scan positions themselves are selected so that they are arranged in a chain named ´*scan chain*´ (Fig. 4b). The distance between individual scan positions in the chain is set for the outdoor positions to a mean of 10 meters, about the same distance as to the measured façade (Fig. 3a). Inside the building, the distance of the scan positions in the chain is reduced to a mean of 5 meters. To link individual rooms a scan positions usually is set in the door frame. These relatively small distances make it possible to reduce the scan shadows to a minimum and to guarantee sufficient overlapping areas for the automatic registration of the scan positions to each other. Additional scan positions are inserted in the chain at building corners and passageways to ensure sufficient overlapping of the data for the automatic registration. It is recommended, although not absolutely necessary, to measure control points during the first and last scan of a scan chain. In general, it is recommended to measure a polygon course with a total station ahead of the scan project. The retro-reflecting foils used to mark the control points are finely scanned with the laser scanner. These few but well distributed control points have a high significance for the resulting accuracy of the point cloud.

For the scanning of free-standing buildings, it is recommended to start outdoors scan around the building in a closed loop at the beginning. Afterwards, scanning is done from a building entrance back outdoors. If the scanner has to be restarted - for example after a change of day - the first scan should be taken as close as possible to the last scan position. This enables a direct connection to the chain for the automatic registration process. The scanner position itself normally is changed within 20-30 seconds. This ensures that the data of the built-in “initial measurement unit” (IMU) provides a good approximation of the positioning for the automatic registration even in the case of poor GNSS signal reception.

a) *b)*

Fig. 3. a) Two colored laser scans, distance between the scan positions approx. 10 meters; b) RIEGL VZ-400i terrestrial laser scanner combined with a Nikon D-810 digital camera and a GNNS receiver

Automatic registration of the scan positions

In order to prepare the scan data for subsequent registration process, the irregular point cloud is resampled in a first step to a fixed 3D grid - the *´3D voxel data set´* (Fig. 4a). The critical parameters for the automatic registration are the voxel size, the amount of voxels involved and the automatic adaptation to the project. The voxel size can be adjusted manually to the respective scan scenario (Tab. 2), but can also be selected automatically by the algorithm.

Table 2. Typical voxel size and amount of voxels for respective scan scenarios

scan scenario	voxel size	amount of voxels
Indoor small	0.05 m	512
Indoor large	0.10 m	512
Outdoor urban	0.25 m	512
Outdoor non-urban	0.50 m	512

A voxel is only generated if it is occupied by at least three measuring points. Thus it is possible to estimate flat surface pieces in the voxels and to represent them by their center of gravity and normal vector. For each voxel the mean value of the reflectivity, the number of measuring points and a format attribute (line, plane, and volume) are stored.

The following data of the individual scan position are to be used for the registration process:

- GNSS position - not always available (optional with RTK solution)
- orientation from accelerometers and magnetic field sensor (reliable roll and pitch, unreliable yaw)
- position and orientation from IMU data relative to previous scan position
- Barometer if GNSS height was not measured accurately enough

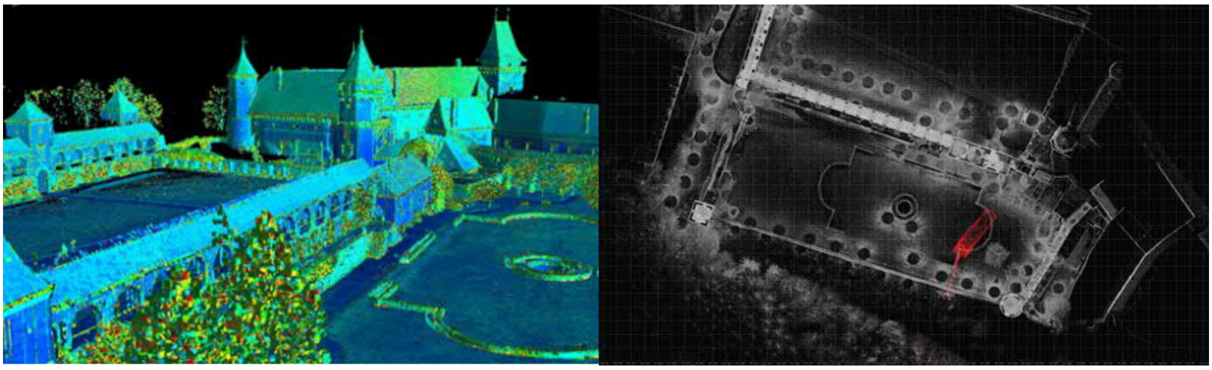
They are combined with reference data from already registered scan positions:

- *´voxelized´* 3D data

The registration process itself then takes place first in the *´spectral range´* known also as *´Phase-Only Matched Filtering´* as presented in [Ullrich 2017]. The following seven-step-workflow has been developed:

- resampling of irregular point cloud on 3D grid yields to "voxelized" 3D data: $v(\mathbf{x})$
- Fourier transformation of $v(\mathbf{x})$: $V(\mathbf{k})$
- same signal but rotated and shifted: $w(\mathbf{x}) = v(\mathbf{Rx+t})$
- Fourier transformation of $w(\mathbf{x})$: $W(\mathbf{k})$
- Fourier Rotation Theorem and Fourier Shift Theorem: $W(\mathbf{k}) = V(\mathbf{Rk}) \exp(i2\pi\, \mathbf{k}^T \mathbf{R}^{-1}\mathbf{t})$
- magnitudes only: $|W(\mathbf{k})| = |V(\mathbf{Rk})|$ → **rotation matrix R**
- for R equal to identity matrix (no rotation): $W'(\mathbf{k}) = V(\mathbf{k}) \exp(i2\pi\, \mathbf{k}^T\, \mathbf{t})$ → **translation vector t**

After this spectral-based registration process has approximated the scans by the order of a voxel size, the extracted planes are used to register the last two scan positions to within a few millimeters of each other.



a) *b)*

Fig. 4. a) Voxel data set of multiple scan positions; b) Resulting point cloud from several scans recorded in a ´scan chain´. The circular features visible in the point cloud indicate the scan positions

This type of reflector-less registration process was initially designed in 2017 and has since been intensively tested in several real scan projects. It is characterized by a very high degree of robustness if the recommendations for the layout of the scan chain and the logistics of the scanning process are followed. Applying this newly developed workflow hundreds of scan positions can be automatically registered. This is a special importance for scan projects like the recording of tunnel systems without ambient light and missing GNSS reception or for example in forests without respective flat areas supporting the automatic registration process.

Multi-station adjustment of scan positions

After the successful registration of all scan positions, small gaps may occur, among other things, if the loop defined by the scan chain is closed. The newly developed algorithm *´Multi Station Adjustment 2´* implemented in the native *RiSCAN PRO* software is recommended in order to compensate for these gaps. This algorithm accomplishes a rigorous adjustment by means of scan data, GNSS measurements and scanner-internal sensor data and all available control points. The average calculation time per scan position is about 20 seconds. Finally, a detailed report is generated automatically.

The scan data can subsequently be checked visually in the 3D view of the resulting voxel data set (Fig. 4a). The standard deviation of the resulting plane estimates from different scans within a voxel is displayed in color. The deviations are usually in the millimeter range. In the project Rosenburg, only four control points were measured with a total station. The multi-station adjustment calculated a standard deviation of 8.7 millimeters for the four reflectors measured by the total station and laser scanner respectively.

ULS – UNMANNED LASER SCANNING

Data acquisition – logistics, specifications and work flows

A *RIEGL* VUX-1 UAV laser scanner (VUX data sheet 2019) on a RiCOPTER UAV (Amon et al, 2016) was used to record the unmanned laser scan data (Table 3). The complete system consists of the laser scanner which is tightly coupled with a high-precision *Applanix* AP20 IMU-GNSS unit for the acquisition of a trajectory with time stamped position and orientation values. For parallel image acquisition two *Sony* Alpha 6000 cameras were used, which are directed obliquely downwards. For processing the trajectory, a GNSS base station was set up, which records a RINEX data stream [Gurtner and Estey 2007] over the time of the recording:

Table 3. Specifications of the unmanned laser scanning (ULS)

Unmanned laser scanner	*RIEGL* VUX-1 UAV
Laser impulse repetition rate	550 kHz
Field of view of the scanner	330 degrees
Scan speed	200 scan lines per second
Precision	5 mm @ 150 m (as given in the data sheet)
IMU-GNSS unit	Applanix AP20
Photo cameras	2 x Sony Alpha 6000
Photo resolution	24.3 MPixel per camera
UAV plattform	*RIEGL* RiCOPTER

After initialization processes, the RiCOPTER (Fig. 5b) executes a pre-programmed flight path for the detailed scan data acquisition. One flight was performed at a flight altitude of 50 meters above ground at a flight speed of approximately 5 m/s. In order to minimize scan shadows on the roof landscape, the flight consisted of several overlapping scan stripes. The flight lasted approximately 30 minutes including the initialization process.

Processing of ULS data

To process the ULS data, the raw data of the IMU GNSS unit and the RiNEX data of the base station are read in the Applanix POSPac software and a resulting high-precision trajectory is created using algorithms known as ´Kinematic Ambiguity Resolution´ [Scherzinger and Hutton 2010].

Based on the time stamps of the trajectory and scan data, the first point clouds are created with an absolute and relative accuracy within the range of a few centimeters. For maximum relative accuracy, the point cloud is further improved with the *RIEGL* software *´RiPRECISION´*. It analyses the corresponding planes between the individual flight strips and uses them to calculate new, improved trajectories, taking into account the local GNSS accuracies. Using the time stamps the images acquired by the *Sony* cameras are also placed along the trajectories and used to colorize the final point cloud (Fig. 5a).

a) *b)*

Fig. 5. a) UAV scan data – true color; b) left: RiCOPTER with RIEGL VUX-SYS laser scanner, right: RIEGL VZ-400i terrestrial laser scanner

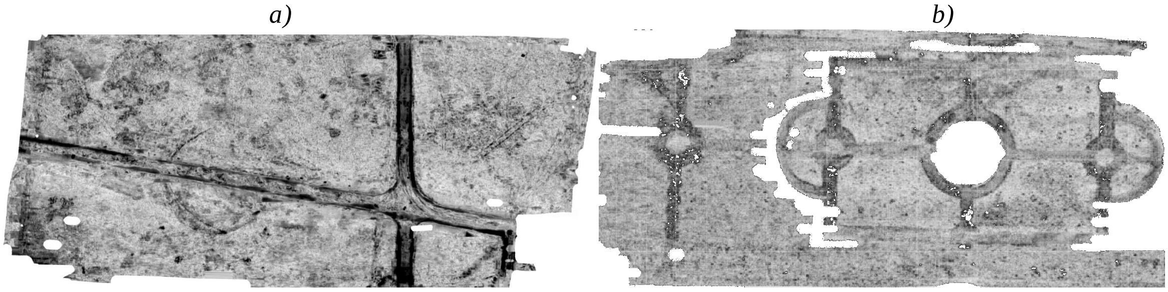
GROUND PENETRATING RADAR

Data acquisition – logistics, specifications and work flows

The GPR measurements on the open areas of the Renaissance castle Rosenburg were completed within a single day applying logistics and workflows developed by the LBI ArchPro for large area high-resolution surveys [Trinks et al. 2018]. The tournament ground was examined with a motorized MIRA (**M**ALÅ **I**maging **R**adar **A**rray) system from Malå Geoscience AB adapted by the LBI ArchPro (Fig. 6a). The MIRA GPR system is based on an antenna array consisting of 17 radar antennas (9 transmitter antennas, 8 receiver antennas) with a center frequency of 400 MHz [Trinks et al. 2010]. The antennas are arranged in a box in two rows, which are shifted by half the antenna width (9 transmitter and 8 receiver antennas. Each receiver antenna registers the signal from two adjacent transmitter antennas resulting in a survey resolution of 4 x 8 cm. The MIRA is mounted on the front hydraulic of a communal versatile tractor from Kubota. A Javad RTK-GNNS system (consisting of base and rover) was used to determine the position of the antenna array with an accuracy of ± 2 cm. The data acquisition and navigation was supported by the software LoggerVIS developed by the LBI ArchPro [Sandici et al. 2013].

The garden terrace was scanned initially with the MIRA with a mean penetration depth of 2.2 m and additionally resurveyed to enable deeper penetration with a Pulse EKKO® Pro handheld system from Sensors & Software applying a shielded 250 MHz antenna (Fig. 6b) reaching up to 3.75 m penetration depth. The GNNS data (geographical coordinates, ETRS 1989) are projected by the data recording software into the reference system ETRS89 UTM 33N.

a) *b)*



c) *d)*

Fig. 6. a) Motorized 16-channel 400 MHz GPR system MIRA mounted on the front hydraulic of a Kubota tractor surveying the tournament ground. b) Hand-held Pulse EKKO Pro 250 MHz GPR system resurveying the deeper layers of the garden terrace. (Photos: LBI ArchPro) Lower row: GPR depth slices of the c) the tournament ground (depth: 0.2 – 0.5 m; area: 0.5 ha); and the d) the garden terrace (depth: 0.2 – 0.4 m, area: ca. 0.5 ha)

Processing and visualization of GPR data

Processing and visualization of the data, both in the field and in post processing, were conducted with the developed software ApRadar developed by the ZAMG and the LBI ArchPro [Trinks et al. 2018]. Several automatic as well as semi-automatic processing algorithms were applied to produce georeferenced and optimized grayscale images. Band-pass frequency filters, time-shift trace corrections, amplitude gain corrections, average-trace removal, outlier detection and noise suppression, as well as envelope-trace computation were performed, before the individual GPR profiles were merged and binned into three-dimensional data volumes. Using selective GPR pulse velocity analyses through hyperbola matching, appropriate values for time-to-depth-conversions were obtained. Subsequently, horizontal amplitude slices, so called GPR depth-slices, were extracted from the 3D data volumes to generate stacks of georeferenced grey-scale TIFF images.

The horizontal depth-slices (Fig. 6c; 6d) were generated in varying thickness [5, 10, 20, 30, 40, 50] cm and the image stacks used for animated image sequences. For further archaeological interpretation and analysis of the data, the resulting stacks of grayscale images derived from the GPR data were imported using the native geodatabase format into the “geographical information system” (GIS) ESRI ArcGIS 10.2. Data segmentation, feature extraction and classification form the basis of the interdisciplinary interpretative mapping process outlining structures of archaeological relevance. Archaeologically relevant anomalies were outlined on the animated image sequences of the depth slices during the interpretative mapping process applying the ArcMap extension *ArchaeoAnalyst* developed by the *LBI ArchPro*. The specially developed extensions overrule ArcMap and enable for the animation of GPR depth-slice mosaics during editing mode.

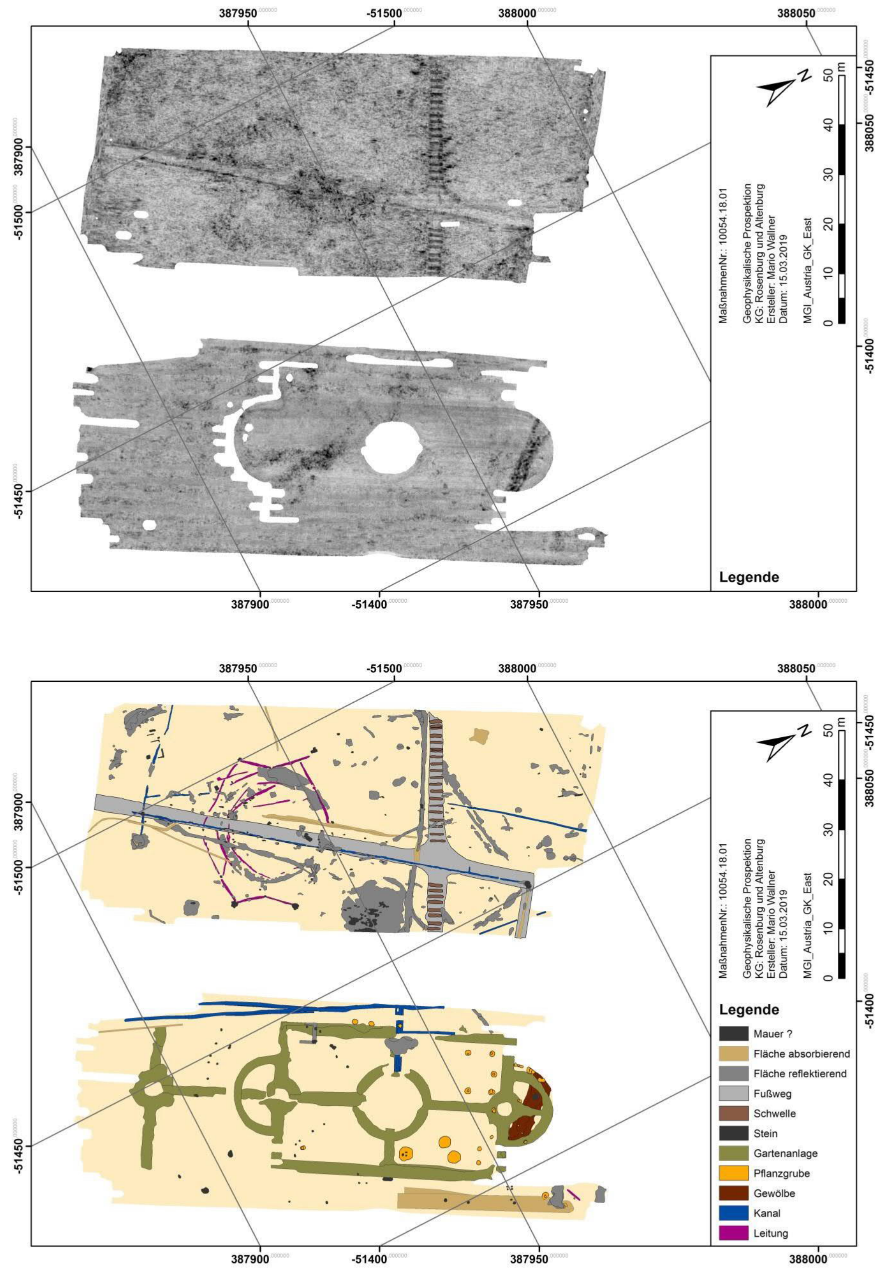


Fig. 7. GPR depth slices of the tournament ground and the garden terrace (depth: 1.4 – 1.6 m, area: ca. 1ha) and archaeological interpretation map

Archaeological Interpretation of the GPR data

The radargram of the tournament ground clearly shows the anomalies caused by the modern road embankments (Fig. 7). In the upper depth range a circular anomaly is noticeable. It is the footprints of a larger tent-like pavilion that has been used over several years for various events. In addition, there are other modern interferences of different installations, which cannot be interpreted in more detail. Due to the high quality of the data, it can be clearly concluded that there are no remains of medieval buildings in the large courtyard. This means that the extension of the castle towards the south did not take place until the construction of the tournament ground.

Under the modern path, which runs almost north-south, massive anomalies can be seen at a depth of approximately 1.4 m to 1.6 m (Fig. 7, dark brown). They lie at regular intervals across the path. However, this is not a disturbance caused by the modern path, but rather an older route for a transport railway, which has been cut into the bedrock. The massive anomalies are caused by the sleepers used to install the rails for this conveyor. It can be traced north up to a quarry located outside the castle. It can be assumed that this transport railway was used in the course of the construction of the garden terrace to procure the material necessary for the embankments.

The radargram of the garden terrace (Fig. 6c; Fig.7, green) clearly shows path embankments of historical gardens which, with a few exceptions, have vanished today. In addition to the paths and pipes for water fountains, the data also clearly show the planting pits for larger trees (Fig. 7, yellow). This planting of larger trees can also be seen in historical illustrations of the gardens, some of which have a different layout compared to the GPR result. Particularly noticeable is an anomaly running almost north-south, which only appears in the deeper layers (> 1.2 m) and widens with increasing depth (Fig. 7, dark red). This is a large vaulted room, accessible from the outside through a narrow entrance below the terrace wall). It has a ventilation shaft which is also clearly visible in the laser scan data (Fig. 8, top). The combination of the vault scanned with the terrestrial laser scanner with the radar data shows a very good correspondence, which clearly shows the potential for the exact definition of cavities in the radar data even at greater depths.

COMBINING TLS, ULS AND GPR DATA SETS

For the comprehensive combination of all data sets the native scanner software *RiSCAN PRO* was extended accordingly to integrate TLS, ULS and GPR data into one view. The developed interface allows for the integration of image stacks as delivered from the GPR prospection. For the direct combination of the data in the same format, an interface to convert the 3D GPR data volume into a point cloud was implemented enabling a straightforward combination for future projects.

In order to register the ULS point cloud on the terrestrial scan data, planes with the corresponding normal vector are extracted. In the subsequent *´Multi Station Adjustment´*, this enables a compensation based on the *´Iterative Closest Point´* algorithm [Dold 2010]. The TLS dataset was recorded and the ULS-based scan data was rigidly shifted. The standard deviation of the residuals from both data sets is 10 mm after registration.

The terrestrial laser data was acquired with the WGS84 geographical coordinates from the GNSS receiver on top of the TLS Scanner, the UAV-laser data had WGS84 geographical coordinates from the used base station and the GPR survey was conducted in WGS84 coordinates in the local UTM zone 33N, thus directly enabling the georeferenced data to be combined in the same coordinate system. The resolution of the GPR data (4 cm x 8 cm x 5 cm) was the coarser than the point clouds from the laser scanning which were adapted accordingly for the combined views. In order to combine datasets of different coordinate systems at their correct geographical position *RIEGL* uses a tool named *´GeoSysManager´*. GeoSysManager is a database tool that allows for the download and the creation of definitions of various coordinate systems along with transformations between their respective data. Accessing these definitions it is possible to calculate the global position of a locally defined dataset allowing it to be placed correctly along with differently referenced datasets. Using that same database it is also possible to further export georeferenced data in various different coordinate systems without the need of additional measured targets to perform the transformation.

The complete project is saved in a new, storage-friendly native format, which can be stored on a server. This allows multiple users to simultaneously extract accurate and detailed information on the castle above and below the surface.

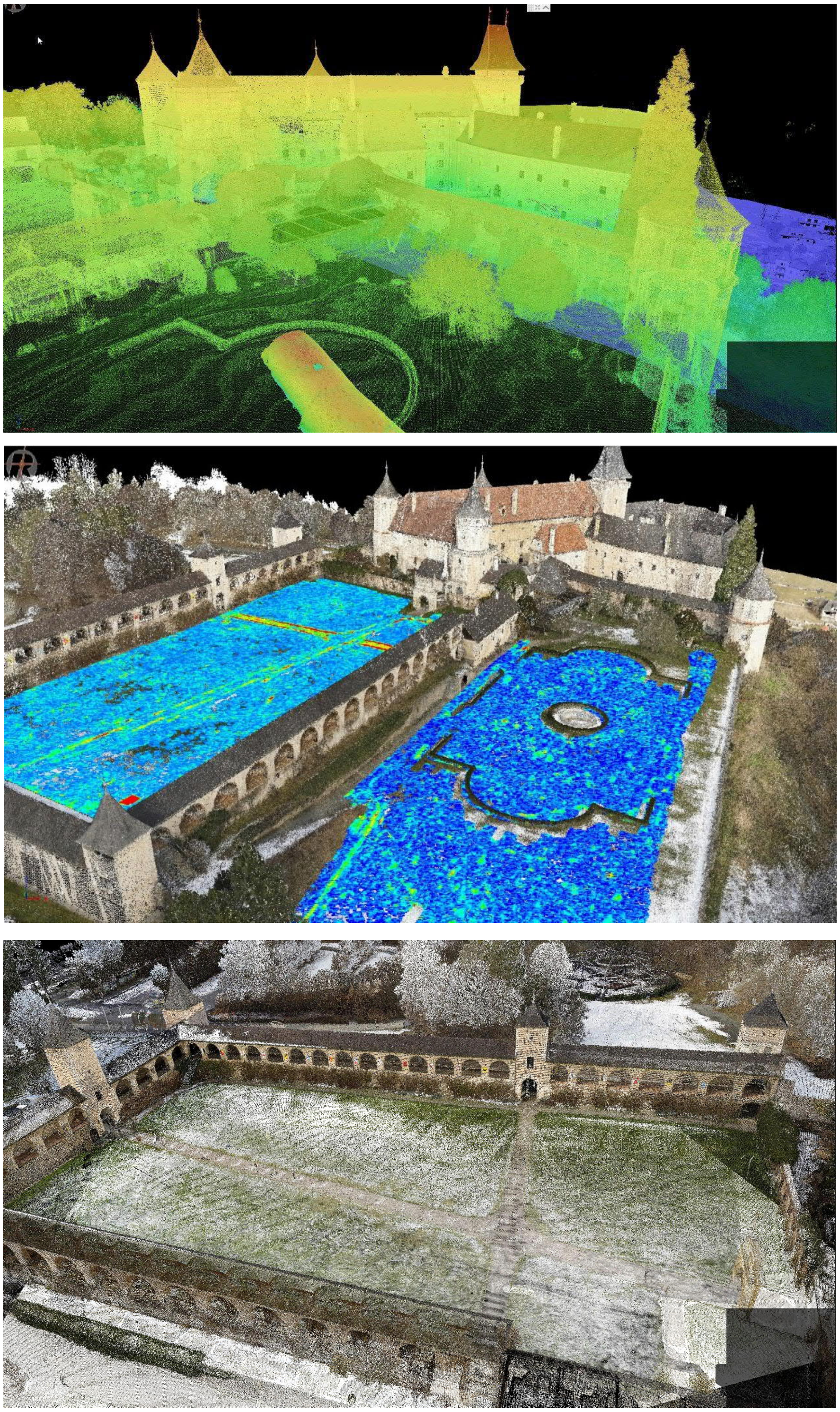


Fig. 8. Combined 3D views of the three datasets. Top: Combination of ULS and TLS datasets focusing on the vaulted chamber underneath the garden terrace. Middle: Combined colored point cloud from the terrestrial and unmanned laser scanning with integrated color coded 3D data volumes derived from the GPR surveys. Bottom: View of the colored point cloud of the tournament ground with GPR depth slice in the depth of 1.4 – 1.5 m below surface depicting the sleepers used to install the rails for the transportation railway

CREATION OF ORTHOGONAL VIEWS AND SECTIONS

A combined laser scanning and GPR project as presented includes dense data from above and below the surface of the investigated site. The point cloud representation of the combined data sets provides a perfect representation of the geometry. The big data contains a lot of information that needs to be comprehensively extracted for further processing or the direct needs of the various users involved in cultural heritage management [Torrejón Valdelomar 2016]. Two-dimensional plans in CAD vector format have long been a common form of comprehensive representation and data exchange among heritage managers, archaeologists, architects etc. The easiest way to create such CAD plans from an existing combined 3D data set of a respective site or historical building(s) is to use an orthogonal view of a point cloud (Fig. 9). This is easy to interpret and can be relatively easily redrawn into a vector graphic. This manual approach has been standard for years but involves expert know how and respective training.

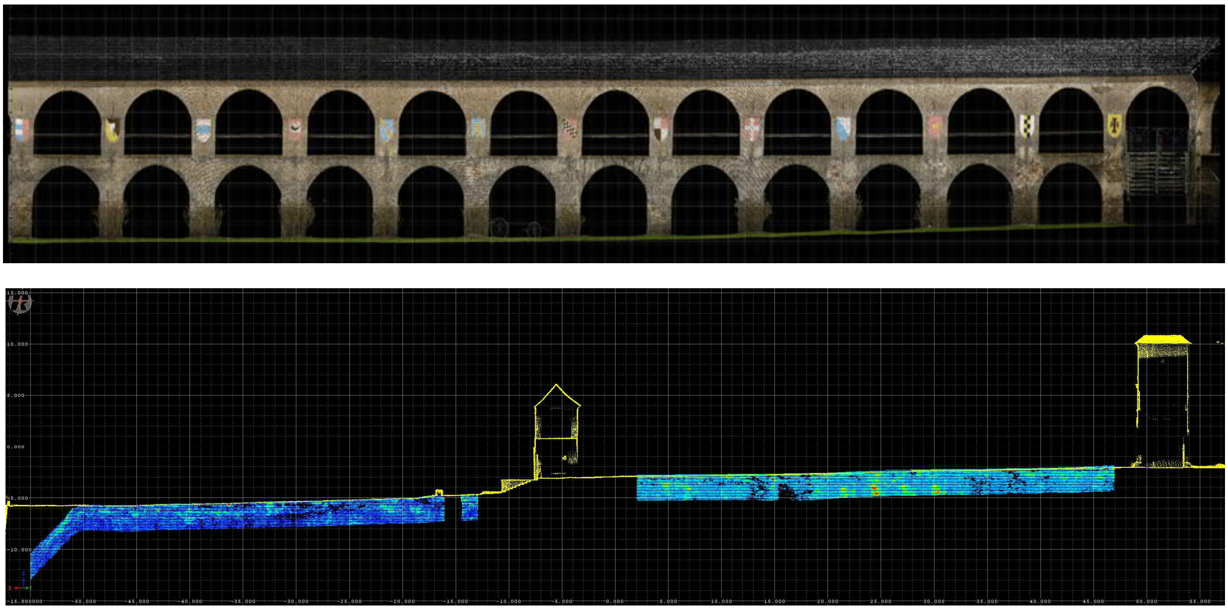


Fig. 9. Orthogonal views and sections from the combined point cloud of multiple scan and GPR data generated by the software RiPano(top) and RiSCAN Pro (bottom)

A solution for the demand for a dynamic and comprehensive creation of appropriate products from these data by non-experts had to be specified. A first implementation focusing solely on the laser scan data is the newly developed software *´RiPANO´*, which enables the export of a complete scan project in such a way that even amateurs can intuitively navigate from the panorama view of one scan position to the next. The browser based intuitive solution [RiPANO 2019] allows for easy data exchange and distribution for the use by non-experts. For each panorama image derived from the respective scan position a depth value is stored for each pixel. The depth information enables the user to set markers at certain points and to capture the respective 3D world coordinates, to measure and export distances or paths. The data format allows for a point cloud to be reconstructed at runtime from the depth values and facilitate the generation of views and sections on demand (Fig. 9). A respective solution for the combined scan and GPR point cloud is provided on expert level by the software RiSCAN PRO (Fig. 9, bottom)

SUMMARY AND CONCLUSIONS

We described a series of workflows and preferred logistics for the fast, efficient and complete 3D recording of archaeological or historical sites above and below the ground surface. The straightforward combination of TLS, ULS and GPR data sets combines surface and volume data in a common coordinate system and facilitates the joint analysis of the 3D digital record. The presented case study, the complex site Rosenburg, exemplifies the challenges and respective solutions found by the interdisciplinary team. An automatic and robust registration method for terrestrial scan positions based on respective logistics and workflows applying the latest terrestrial laser scanner

RIEGL VZ400i are presented. Only the combination of the terrestrial scans with the unmanned aerial scans provides a complete record of the scanned surface. In order to solve the problem of the removal of the disturbing vegetation, the possibility of waveform processing provided by the selected state-of-the-art laser scanners was an essential prerequisite. Laser scanning was preferred to photogrammetric solutions, since on the one hand a faster generation of the point cloud could be achieved [Studnicka et al. 2013]. On the other hand, the accuracy over the entire point cloud is considered constant and < 1 cm and the registered point cloud is georeferenced per se. In contrast, the result of photogrammetry is a priori without scale and with varying accuracy. The power of laser scanning for the recording of surfaces contrasts with the power of photogrammetry for the definition of edges. Through the massive overlapping of scans, the definition of edges is enhanced and comparable with a photogrammetric record from comparable distances.

We present for the first time a standardizable solution for the combined visualization and detailed analysis of laser scan data and high resolution GPR volumetric data sets implemented into a single software product *RiSCAN PRO*. The newly developed and presented software *RiPANO* enables the non-expert handling, distribution and shared analysis of such complex 3D scan data sets. A respective solution for the combined scan and GPR point cloud is currently only available on expert level applying the software *RiSCAN PRO*.

The case study presented and the solutions worked out in response to the challenges encountered show that high-resolution and detailed documentation of archaeological and historical sites is possible in the shortest time without disregarding the quality as measured by the highest accuracy and resolution. This opens up a new window for the efficient digitization of our cultural heritage above and below the surface, which is particularly important for endangered sites, as digitization projects can be started and completed immediately. The improvements to making the data available to non-experts in an appropriate and comprehensible form are of particular importance for their sustainable and dynamic use in the field of Culture Heritage Management as well as in the area of development.

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