Long Paper

3D Modelling of the Castle Neu-Wildon

Applying Drone-Based Photogrammetry, Terrestrial Photogrammetry and Terrestrial Laser Scanning – a Comparative Study

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Abstract: Different reality capturing techniques are available for every price segment nowadays, from quick and easy solutions up to highly accurate surveying gear for detailed 3D documentation. However, every technique beholds its advantages and disadvantages and the performance varies through use-cases at different scales. In 2021, at the castle of Neu-Wildon, terrestrial and drone-based photogrammetry as well as terrestrial laser scanning have been applied by geodetic experts for documentation purposes. The different data sets have been used to perform a comparative study for building research. The paper discusses on the one hand the benefit of the highly accurate 3D point data from the Leica RTC360 and on the other hand the good feature resolution of the Nikon D800 SLR images. Due to the removal of the vegetation for extended conservation work, also a drone mission with a DJI Phantom 4 was performed and evaluated. Additionally, the usability of the 3D data sets for building research is demonstrated at the example of the virtual reconstruction of the site. The walls and floors have been modelled in 3D and checked for feasibility with virtual reality gear. The result is a visualisation of the current working-hypotheses for the appearance of the castle Neu-Wildon at the end of the 16th century.

Keywords: *Laser scanning–UAV–Photogrammetry–Neu-Wildon–Digital Twin, Reconstruction.*

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Introduction

Medieval castles still demonstrate the historical importance of locations throughout the country and are major landmarks. Due to the predominantly martial appearance of the ruins and a romanticization of the theme in the 19th and 20th century they have often a negative association with warfare, knights and fairy tales in the public perception.

a) b)

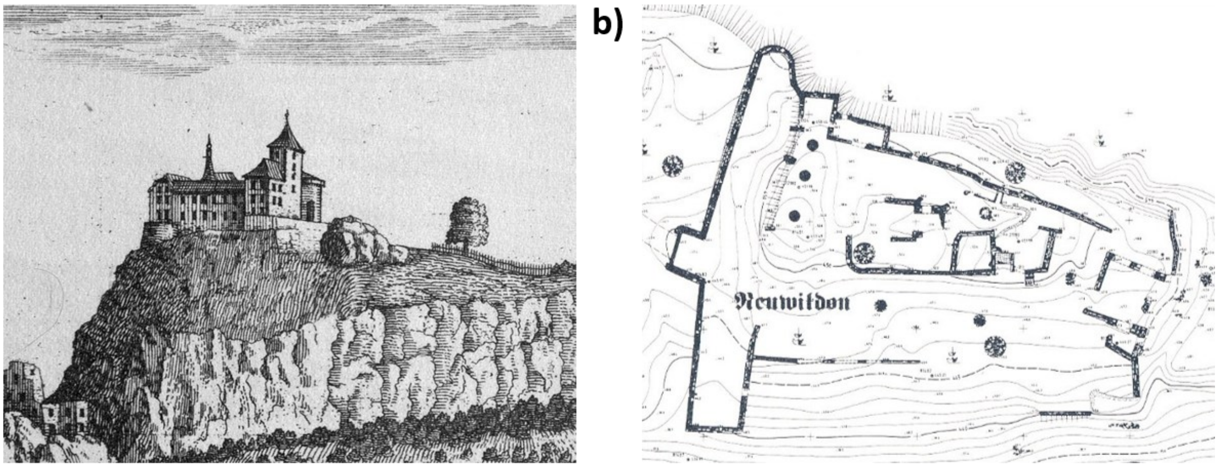

Fig. 1. Shows a) a Copperplate of Georg Vischer 1681 in Baravalle (1961) and b) a 2D plan (© TU Graz 1981).

Due to this high regional relevance, there is a public interest in the cultural heritage of these ruins and therefore it should be the common aim to provide them a contemporary place in the modern society as local recreation area, event centre and research object.

The castle of Neu-Wildon is located in the southern part of Styria on the castle hill right above the settlement of Wildon. According to Baravalle (1961) it was first mentioned in 1260 although Romanesque pillar fragments indicate a predecessor building, this may explain the epithet “new” in Neu-Wildon. The fortifications of the castle have been extended in several building phases. In the 16th century the castle complex consisted of an inner castle and an outer castle with a bridge over the defensive ditch. Although major late gothic adaptions have been made in the early 16th century the castle was in a devastating condition at end of the same century so that major renovation work had to be applied in 1594. Soon afterwards the castle lost its military function in 1624 and was transformed into a Renaissance living place which can be seen in Georg Vischer’s copperplate from 1681 in Figure 1a. After a new palace was erected in the nearby community the castle on the hill lost its importance and was used as a jail and storage room in the 18th century. In 1810 a lightning hit the castle, which burned down the roof and the wooden interior which left the castle inhabitable and was therefore abandoned and left to decay.

As documented by the Austrian cadastre records throughout the 19th century, the walls soon collapsed after the roof was gone and the complex had nearly reached todays observable state at the beginning of the 20th century. Nevertheless, Neu-Wildon has drawn the attention of researchers for generations. It was Otto Piper (1902), who first drew 2D plans of the site and started the scientific investigation. Extended archaeological excavations from 1985 to 1988 revealed the prehistoric importance of the castle hill and excavations from *Kulturpark Hengist* dealt with the construction of the medieval castle itself.

However, in 1981 a team from the geodetic department of Graz University of Technology (TU Graz) first applied modern surveying techniques to produce an accurate 2D map of the whole site, which can be seen in Figure 1b.

a)  b) 

Fig. 2. Situation a) with (© wehrbauten.at) and b) without vegetation in 2021(© Kaufmann)

In 2021 conservation work had been applied to the complex to prevent the remaining walls from collapsing and to preserve the site for future generations. For the conservation work the dense vegetation, which can be seen in Figure 2a, was entirely removed. The situation after the clearance of the vegetation (Figure 2b) was the unique opportunity for the documentation of the cultural heritage. Therefore, it was again a team of Graz University of Technology in cooperation with the University of Graz, who for the first time have applied a state-of-the-art full 3D documentation of the castle remains.

Aim of the 3D documentation and the comparative study

The restoration company required a rectified orthographic map of the site and detailed orthogonal wall plans for documentation purposes. 2D plans of the walls are still common practice in all fields of archaeology as they allow a detailed inspection of the used brickwork and the investigation of building phases. However, the 3D relation between the wall segments on the plans is lost which may lead to difficulties in the interpretation by future scientists if the original site has disappeared. To provide a full 3D digital representation of the castle the production of a virtual 3D model (digital twin) of the current state of the castle was foreseen. The obtained 3D model should also be the starting point for a virtual reconstruction attempt of the appearance of the original castle at the end of the 16th century.

In modern surveying a broad spectrum of 3D techniques is available for documentation of cultural heritage. Photogrammetry and laser scanning are the most common technologies in an archaeological context because of the high object resolution and the generation of true colour textures. Especially photogrammetry has faced a real boost in the industry because of the use of low cost equipment and easy-to-use software. The usage of consumer grade single lens reflex (SLR) cameras and drones for the consumer market have made this technology affordable for a wide range of users even without a surveying background.

Despite the algorithmic advances in modern structure from motion (sfm) software the basic geometrical limitations of the bundle adjustment and a sloppy data acquisition on site easily result in a significant accuracy loss. Because of the resulting high-resolution models these systematic errors are nearly impossible to reveal visually without any external ground truth.

A laser scanning session on the other hand is more cost-intensive, which results in a smaller number of users. However, the polar measurement principle with an active laser source delivers a more homogeneous output compared to photogrammetry. Also the resulting accuracy can be better assessed. Nevertheless, the accuracy of a laser scanner is also affected by instrument errors, atmospherical disturbances and strongly related to the surface properties (e.g. penetration of wood and marble). Systematic errors between different types of laser scanners are investigated in the COLLECTOR[1] project in more detail.

The different behaviours of survey technologies result in different output qualities. To discuss and evaluate the usability of the different methods in building research the site of Neu-Wildon has been surveyed with terrestrial photogrammetry, drone photogrammetry and terrestrial laser scanning. Each technology is able to individually produce a 3D model of the scene, which can be compared with each other by means of resolution and accuracy.

Applied methods for 3D documentation

Control network

The foundation of every survey has to be a network of control points with superior accuracy to stabilize the registration process of the acquired raw data (images and scans).

Laser scans can be co-registered by applying cloud to cloud algorithms like the iterative closest point algorithm (ICP). However, these approaches are likely to fail when lacking of significant corners in the scene and uncertainties accumulate very fast. Regarding photogrammetry, also by using industrial grade drones with a geodetic global navigation satellite system (GNSS) receivers the geometry of the resulting 3D model can also be stabilized by the known exterior orientation of the taken images. This only applies if the camera locations are well distributed in height and location over the scene and is limited to the achievable accuracy of dynamic GNSS measurements. To reach a reasonable accuracy of one centimetre or below the usage of ground control points is inevitable for both technologies even with a high-grade surveying equipment.

The determination of ground control points within millimetres can only be accomplished with a geodetic total station. On the site a geodetic network has been established with 17 setup points which have been linked with redundant measurements. The redundant measurements have been adjusted with a least square estimation and after the application of atmospheric corrections a single point accuracy has been reached of 1 mm up to 2 mm in all setups.

On the basis of this network configuration the coordinates of 19 ground marker plates have been derived for the drone survey and 250 wall markers have been measured for the terrestrial photogrammetry. These control points do not only serve as the geometric reference for all used surveying methods, moreover they define a unique coordinate system in which all measurements are carried out and enable a geometric comparison between the results.

[1]Conference: DVW e.V. (Hrsg.): Terrestrisches Laserscanning 2022 (TLS 2022). DVW-Schriftenreihe, Band 104/2022, Wißner Verlag, Augsburg, At: Fulda, Germany.

Terrestrial photogrammetry

A Nikon D800 SLR camera was used to capture 1088 images from the site. At an average operation distance of 7 m between the camera and the object surface the sensor delivers an object resolution of 1.2 mm per pixel. For the processing of the images with a structure from motion approach the images have been taken with overlapping features in each image and coincidences of the camera centres have been avoided. To overcome systematic errors in the bundle adjustment the images contain a reasonable number of visible wall markers and the image planes have been nearly parallel to the object surfaces, where it was possible. An exemplary distribution of camera positions around a pillar can be seen in Figure 3a. Unfortunately, in narrow corridors with high walls steep steering angles of the camera were unavoidable.

Also the arrangement of the ground control points is crucial for the geometrical accuracy of the final result. The ground control points had to be distributed equally in 3D space throughout the site to scale the model accordingly in each coordinate axis. Mounting the markers at the top of the walls also was a problem. Due to the bad condition of several wall parts the access to the top regions has not been safe with a ladder. Therefore, a sparser distribution has been accepted for the safety of the on-site personal. The mounting of a wall marker can be seen in Figure 3b. Two different sizes of markers have been used (5 cm and 2.5 cm) to sustain the visibility of selected markers also at a higher operation distance.

After the geo-referencing of the images in the structure from motion software the re-projection error indicated a mathematical precision of 0.5 pixels which would correspond to 0.6 mm at 7 m.

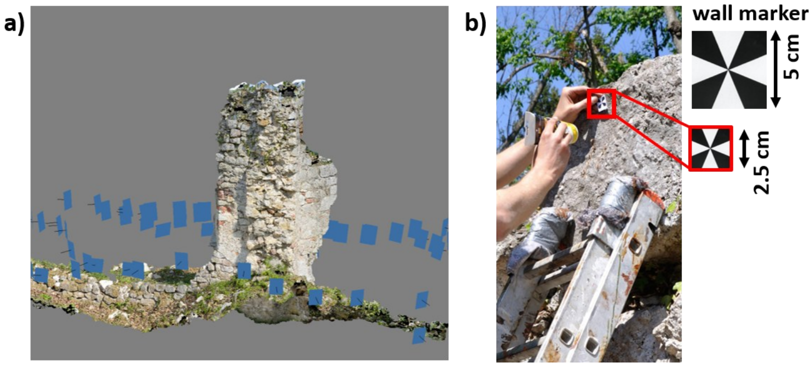

Fig. 3. a) camera positions for the documentatin of a late gothic pillar fragment b) mounting of the wall markers (© Kaufmann).

Drone-based photogrammetry

The internal camera of the DJI Phantom 4 drone acquired 369 digital images with a frame size of 4000x3000 pixels. The pixel size of 1.56 µm relates to a ground resolution of 18 mm at a flying height of 43 m above ground. In the computation of the bundle adjustment 19 ground markers of 30 cm size (Figure 4a) have been taken into account, which resulted in a re-projection error of 1.1 pixels. Therefore, a mathematical precision of merely 2 cm has been reached with the drone survey.

The flight mission was planned in advance and executed automatically. The orientations of the images can be seen in Figure 4a where two groups can be observed. The entire area has been imaged with orthogonal angels with regards to the flight direction. These images have been later used to derive the high resolution orthographic map from the site. To capture also the walls and to derive 3D information the majority of the images have been taken with a steering angle of 45°. The acquisition of parallel images to the object surface has not been possible with an automatic flight mission. The avoidance of object collisions required a certain height above the ground.

Terrestrial laser scanning

The site was scanned with a Leica scanner RTC360 with 49 setups. According to the instrument's datasheet and proven by internal quality checks the scanner fulfills an accuracy of 1 mm + 10 ppm (e.g. 5.3 mm at 40 m). The alignment of the scans was established with cloud-to-cloud approaches with a minimal overlap of 28%. The scan registration was stabilized with 17 reference points in the scene. These targets (Figure 4b) have been placed with surveying poles on the marked setup points from the control survey. The overall error at the target plates after the network adjustment reached 4 mm.

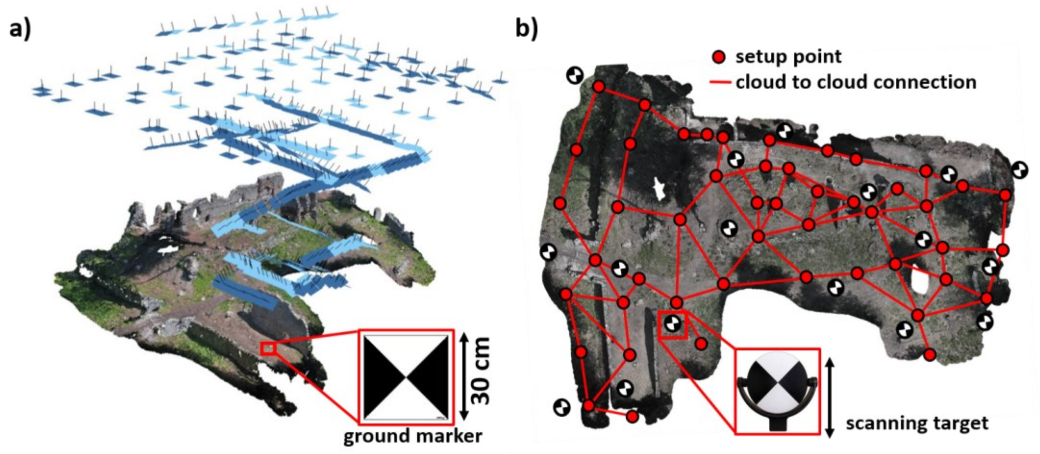

Fig. 4. a) Automatic flight mission with the DJI Phantom 4 (© Kaufmann) and b) setups of the laser scanning session (© Bauer).

Raw data processing and 3D mesh generation

The laser scanner produces unregistered point clouds which require processing with a registration software. In this paper the point clouds were adjusted with the commercial Leica Cyclone Register 360 Software[2] (2021.1.2) on a custom computer (64GB RAM, Intel i9, 3.5GHz, 8GB Graphics). The import, registration and export of the 49 scans has taken nearly 15 hours. The mesh has been produced with the commercial software Leica Cyclone 3DR[3]. Although the software supports an automatic meshing algorithm, the manual removal of the remaining vegetation, resampling and manual mesh optimization took an additional week of working.

The images from the SLR camera and the DJI drone have been processed with *Agisoft Metashape*[4] 1.6.4 on a different workstation (24GB Ram, Intel i7, 3.5GHz, 3GB Graphics). With this structure from motion software the orientation of all images is computed within a bundle adjustment. On the basis of the computed orientations a dense point cloud is derived which can be meshed also inside *Agisoft Metashape*. Due to the higher noise ratio of photogrammetric point clouds the meshing algorithm in *Agisoft Metashape* is optimized for a high degree of smoothing in comparison to *Cyclone 3DR*. The processing of the terrestrial images has taken 100 working hours and the processing of

[2] Leica Geosystems: https://leica-geosystems.com/de-at/products/laser-scanners/software/leica-cyclone/leica-cyclone-register-360

[3] Leica Geosystems: https://leica-geosystems.com/de-at/products/laser-scanners/software/leica-cyclone/leica-cyclone-3dr/

[4] Agisoft LLC: https://www.agisoft.com/

the airborne images has taken 20 working hours. Additionally, a great effort had to be put into the manual masking of vegetation in the airborne images of 16 working hours.

Both meshing algorithms in Cyclone 3DR and Agisoft Metashape produce homogeneous triangles. The sizes are optimized considering the average object resolution of the underlying point cloud in order to avoid holes in the meshes. Therefore, the resolution of the resulting mesh strongly depends on the used software, the object resolution, obstructions in the scene and the degree of smoothing. For the mesh generation the meshing parameters were customized for each software. Figure 5 displays that the meshed scan data and the meshed drone data have led to a comparable mesh resolution although the storage used for the raw data of the scan exceeds the drone survey by far.

raw data		mesh		
format	storage	storage	triangle resolution	texture
369 images	1.8 GB	~ 850 MB	~ 3 cm	image textured
1088 images	24.6 GB	~18 GB	~ 0.6 cm	image textured
49 scans	61.2 GB	~ 700 MB	~ 3 cm	point cloud textured

Fig. 5. Nominal differences in the meshing results of the technologies (© Bauer).

The high resolution of the terrestrial photogrammetry has resulted in the mesh with the smallest triangles and the largest memory size. The 18GB mesh had to be divided into separate meshes in order to be manageable with the mentioned workstations.

The single images of the photogrammetric approaches are blended together for photorealistic textures of the derived meshes. The brightness and contrast in the images is automatically corrected in *Agisoft Metashape* and a homogenous texture is provided. Regarding the laser scanner, the point cloud is colourized by internal cameras. Although the scanner takes HDR images they are not perfectly suitable for texture mapping in *Cyclone 3DR*, because the software does not colour the mapped images correctly. Therefore, the image transitions on the mesh are clearly visible and the low resolution of the images and the limited viewing angles lead to an unsatisfying result. Although the direct colourization of the triangles with the point cloud leads to the lowest texture resolution (resolution of the texture corresponds to the triangle size) the more homogenous result is preferred by the authors compared to any other approach in *Cyclone 3DR*.

Evaluation and comparison of the derived 3D meshes

Resolution

Regarding the scientific inspection of building properties on the basis of a 3D mesh the object resolution is a crucial factor. Two different mesh resolutions have to be distinguished: On the one hand the geometrical resolution (e.g. size and shape of single bricks) and on the other hand the texture resolution (e.g. surface properties).

In Figure 6 representative parts of the resulting 3D meshes are visualised based on different surface types. For judging the quality of a mesh it has to be investigated with removed texture first. The drone mesh is characterised by a rough and noisy surface. This is very representative for photogrammetric outputs with a low camera resolution (resulted by the height above ground) or bad lighting conditions.

The quality of the terrestrial photogrammetry and the laser scan appear to be at the same level. Although the SLR mesh has a much higher triangle number, both meshes have a comparable object resolution and a similar noise level. Regarding the noise level, the laser scanner has the clear advantage of the active laser source. Although the noise ratio grows by distance and is closely related to the surface normals and properties it is more stable compared to any photogrammetric approach. Here, lighting conditions, camera angles and a change in the inner orientation of the camera have tremendous influence on the results.

The highest resolution texture, which is of great importance for the building research, is clearly produced by the terrestrial photogrammetric result due to the small operation distance of the camera. The resolution of the drone supports an orthographic overview image, but a close inspection of the brickwork is nearly impossible. The texture of the laser scan mesh can be used for demonstration purposes only. This is also true for the drone texture, which is insufficient for the scientific documentation of the brickwork.

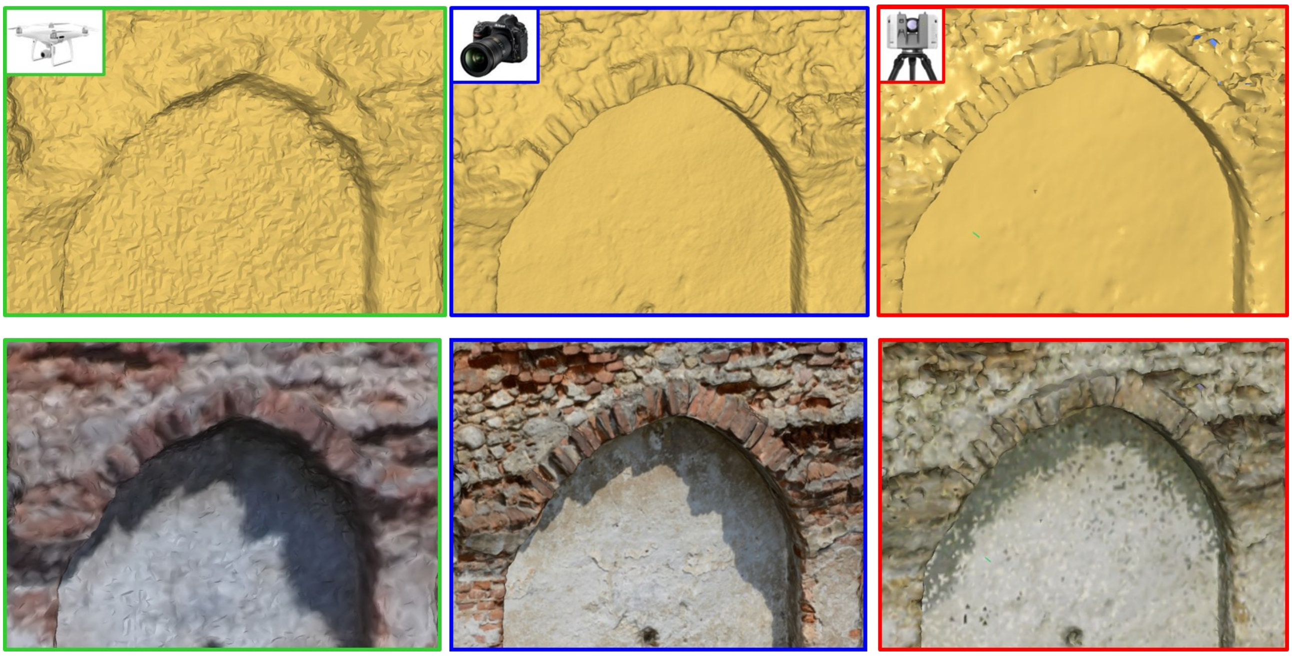

Fig. 6. Comparison of the mesh resolution (© Bauer).

Geometric accuracy

After the processing of surveying data sets quality parameters are provided for the user by the software solutions. These parameters predominantly indicate the mathematical reproducibility of the results, as the re-projection error in Agisoft Metashape or the deviation between the point clouds in *Cyclone Register 360*. The overall systematic errors in the result can only be revealed by external information and are not covered by mathematical precision.

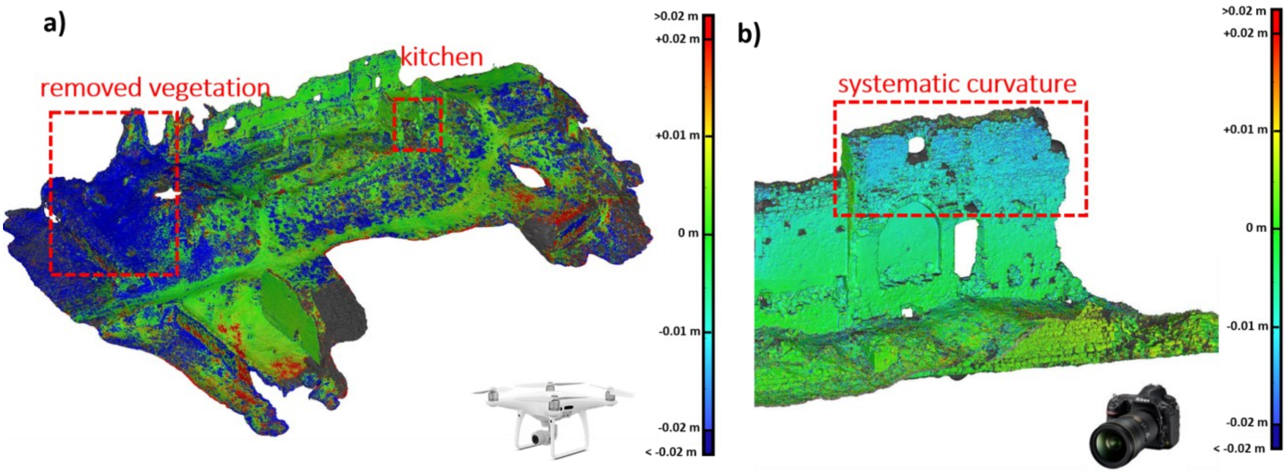

Fig. 7. Comparison of the laser scan point cloud with the a) drone-model and b) SLR model (© Bauer).

For the geometric evaluation of the photogrammetric models the homogeneous laser scan point cloud was used as a reference. The accuracy of the laser scanner of only few millimetres from the adjustment in *Cyclone Register 360* was verified on the basis of the 250 wall markers in the scene.

The cloud (laser scan) to mesh (drone) comparison, which was executed using the free to use software *CloudCompare*[5], shows in Figure 7a that 75% of all deviations are within ± 2.5 cm. These deviations correlate to the pixel resolution of the flight mission and are an expectable result. Therefore, the reached accuracy is acceptable for areas with exposed ground and also for exposed wall parts. The area where vegetation has been masked in the west of the complex still has majyor deviations of up to 5 cm. Nevertheless, the flight mission could not cover obstructed areas such as the central kitchen area or the northern living quarters. The automatic meshing algorithm tried to autofill these holes, but failed because of the high noise ratio in these areas. The failed extrapolation attempts with the resulting bubbles and bumps are quite common in photogrammetric models and lead to deviations far beyond the normal accuracy level. For a scientific product, these extrapolated areas either must be manually revised on the basis of additional terrestrial measurements or the auto filling is disabled and the holes clearly indicate areas without information.

The cloud (laser scan) to mesh (SLR camera) comparison in Figure 7b has a high congruence (few millimetres) in the central area where nearly orthogonal viewing directions were possible. Here the accuracy of both technologies are at the same level and the differences are not significant. However, a systematic curvature can be observed at the top region of the palas wall. This systematic effect of up to 1.5 cm is related to the spatial distribution of the wall markers distribution and the steep steering angles of the acquired images.

Virtual 3D reconstruction of Neu-Wildon

Beside the usage of the point cloud for structural investigations and future deformation analysis, the survey aims to contribution to the building research and should demonstrate the usage of the dataset of the castle for a virtual reconstruction.

The virtual reconstruction required not only geometrical accuracy for the extraction of large-scale feature parts as walls and the terrain but also high resolution for the extraction of small-scale features

[5] GNU GPL: https://www.danielgm.net/cc/

as windows and doors. Therefore, the virtual reconstruction bases on the laser scan mesh as well as on the SLR model.

In general, a 3D reconstruction of a historic building is not an exact process. As the data foundation itself the reconstruction suffers from semantic errors caused by assumptions, logical considerations and misinterpretation of historic sources. The 3D reconstruction in this paper describes a plausible castle complex which is within the tolerance of the historical sources and the castle remains. Nevertheless, due to the state of decay of Neu-Wildon, it summarizes and visualizes ongoing working hypothesis which may inspire further research to prove these hypotheses by systematic archaeological excavations.

Reconstruction of the floor plan

The start of a reconstruction is the definition of an original floor plan. The appearance of the castle complex strongly depends on the usage of the single buildings and the fortification concept.

The building phases of the castle remains can be found in a 2D map by *Kulturpark Hengist* from 2015 (Figure 8a). An historic plan can be seen in Figure 8b from the architect Domenico dell'Allio, which was drawn in 1545, pictured in Fritzberg (1993). Domenico dell'Allio clearly indicated the lost south wall, the shape of the front building with the main tower and displays the shape and location of all gates. However, the map from 1545 has to be seen as a concept paper for further renovations as Domenico dell'Allio was also a famous civil engineer of that time. The displayed bastion and the roundel have never been erected. On the basis of the castle remains and the plan of Dominico dell'Allio the inner castle is well defined with the palas, the late gothic church, the kitchen with the cistern and the front building with the main tower.

More uncertainties arise in the outer castle area. The most prominent structure is a complex integrated into the outer east wall. Although Otto Piper refers to it as "Maierhof", which would indicate a usage as living house for people with administrative functions, it is displayed in a painting from 1730 as a wooden barn and Domenico dell'Allio refers to it as "stable". Also the location in the castle complex and the construction indicate a more likely usage as a storage room for supplies or livestock.

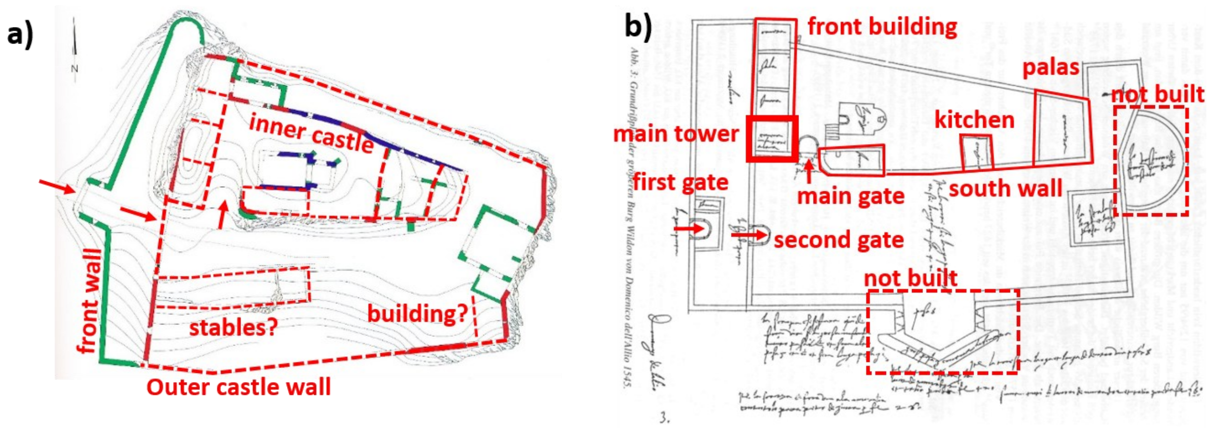

Fig. 8. a) Plan of 2015 (© Kulturpark Hengist[6], extended with information by the authors in red) and b) a map of Domenico dell'Allio of 1545 published in 1993 (© Fritzberg, also with information added by the authors).

[6] Kulturpark Hengist: https://www.hengist-archaeologie.at/archaeologie/fundorte/wildon/325-unterhaus-schlossberg-wildon

In the southern part of the outer castle near the second gate several wall remains are also visible. The usage of these buildings is still unclear. Otto Piper refers to them as stables which is still the most likely explanation with regards to their location and the proximity to the gate. A similar configuration of the stable in the outer castles can be seen in other Styrian castles too.

Building heights and 3D context

The 2D floorplan has been merged with the laser scan model inside the *Cyclone 3DR* environment for modelling. The appearance and the height relations of the inner castle with the main tower and the palas building are visualised in the Vischer copperplate in Figure 1a. Although the large number of windows was implemented in the Renaissance adaptions 1624, the observable number of levels is still valid for the original castle because it correlates with the corresponding older wall parts which are still visible today. The roof concept can also be extracted from Vischer's copperplate and the slope of the roof was assumed with 60°, which is typical for medieval roof constructions.

The height of the south wall of the castle was modelled according to the still existing north wall and under the assumption that the battlements should be reachable by the palas and the main tower. A valuable tool for the logical considerations was the virtual reality gear. During the reconstruction the 3D model was made accessed in *Unity 2019.3.3f1*[7] with the *HTC Vive Pro*[8] to investigate the feasibility of windows and doors from a first-person perspective.

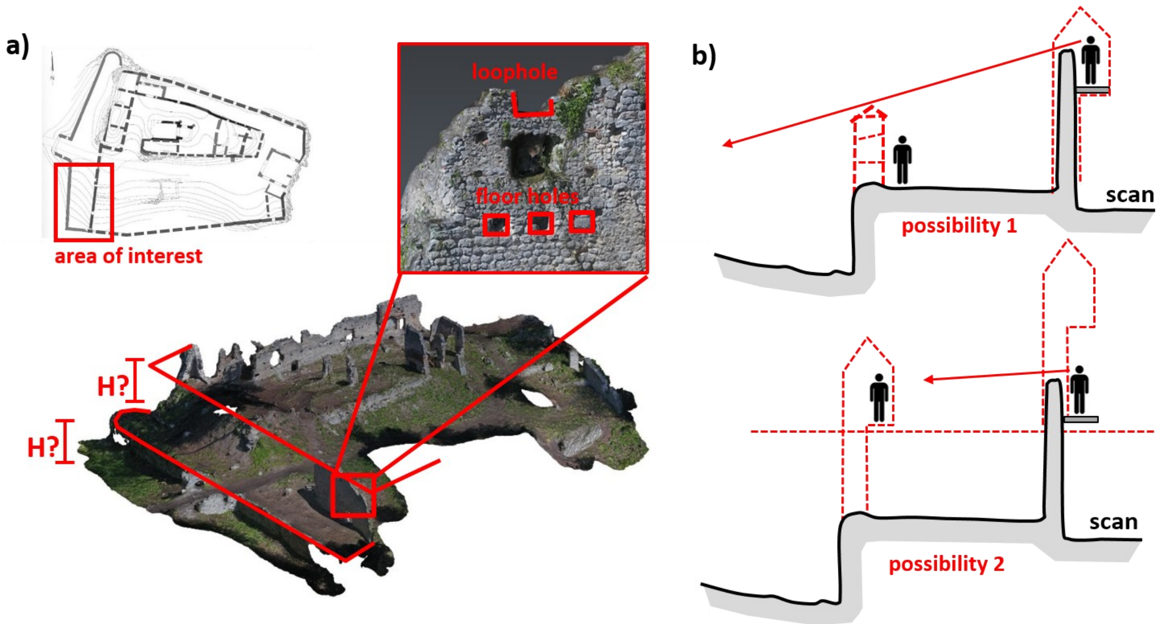

Fig. 9. a) Situation at the outer wall and b) resulting reconstruction possibilities (© Bauer).

A challenging part was the comprehensibly model the appearance of the front wall with the first gate and the wall height of the outer castle. Vischer has not drawn any battlements in his copperplate on the front wall, therefore it is very likely that this wall has already been removed for aesthetic reasons in the renovation in 1624. A hint for the original appearance may be given by the remains of the outer west wall displayed in Figure 9. In a height of 7 m a loophole can be seen in the wall that follows the appearance of the surrounding wall and makes an implementation in younger times unlikely. The

[7] Unity Technologies: https://unity.com/

[8] HTC: https://www.vive.com/de/product/vive-pro/

remains of a wooden platform to hold a person opens up two possibilities. One possibility is that the loophole should enable a view above the front wall or the other possibility is that it should enable a view into the front battlements. Both possibilities have been modelled and plausibility checked with virtual reality gear.

Possibility 1 interferes with the wall height of the front gate and also the majority of the field of view is still obstructed by the front wall which makes it useless for defence purposes. Regarding possibility 2, loopholes at the same height as the battlements in front can be found in other castles to defend nearby passages through the walls. At the Styrian castle Waldstein such passages can be seen to allow defenders to retreat into the inner castle, when the corresponding wall segment had been breached and the gates were inaccessible. Therefore, possibility 2 was implemented into the 3D model and the battlements were constructed according to examples provided by other Styrian castles of that time.

Result of the virtual reconstruction

The 3D model of the reconstruction was modelled in *Cyclone 3DR* by the extrusion of extracted polylines. In addition, object groups as windows and doors were modelled separately (on the basis of the photogrammetric model) and have been inserted into the corresponding location (determined by the laser scan model). The final renderings were done with the free to use software *blender*[9] (Figure 10).

The use of 3D technologies and the survey data lead to a more accurate workflow compared to conventional paper cut models. In addition to the fact that objects can be derived from virtual 3D models, 3D viewers also enable arbitrary viewing points on the data set. In the reconstruction, features do not have to be looked up at images, they can be inspected at the right location within their 3D context. Also, the use of 3D tools as virtual reality (VR) gear is a valuable augmentation for the interpretation of datasets.

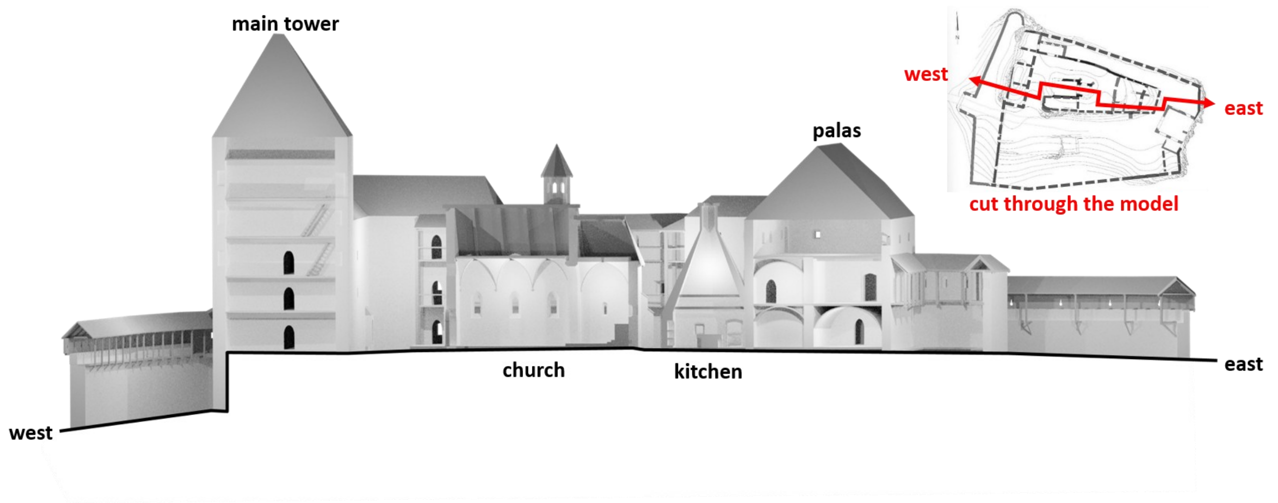

Fig. 10. Virtual reconstruction attempt of the castle Neu-Wildon (© Bauer).

The reconstruction was shared with the castle owner and local residents because there is still a public interest in the remains of the castle Neu-Wildon. Due to the state of decay it is hard for a

[9] GNU GPL: https://www.blender.org/

nonprofessional to get an idea of the original appearance on site. Here the reconstruction may help people to get a notion of the importance of the site and to raise their commitment to preservation.

From a scientific point of view, it is important to point out the quality of the 3D reconstructed model in a similar manner as it applies to the survey models. In Figure 10 a black and white colour map was preferred instead of a photorealistic texture. Such a texture would require detailed records showing the original appearance of the facade and increases therefore the degree of uncertainty in the model. In some scientific publications the degree of uncertainty is expressed by the transparency of objects, which leads to a limited visibility of objects on the other hand and leaves room for misinterpretations.

For future reconstructions the creation of an artificial second texture for models may be advisable which indicates the quality more clearly. The implementation of a colour scale could be foreseen, which is correlated to the ratio of real structure and reconstruction in a building and takes also into account the quality of the historic sources used for the reconstructed part (image or painting, contemporary or not). It should be possible for the user to switch between textures during inspection, which can technically be realized already with 3D environments like *three.js*[10].

Lessons Learned

For all applied surveying methods a high effort was put into the quality management by creating a geodetic reference frame and placing markers into the scene. Nevertheless, there have been limitations that have caused quality losses at certain points of the field work.

Regarding the terrestrial photogrammetry, steep camera angles and limited access of the top regions led to a systematic curvature in the dataset. The usage of a telescope pole could sustain orthogonal viewing angles and may also stabilize the bundle adjustment by images from a higher perspective in future surveys.

The drone-based photogrammetry has shown that with the automatic flight mission a fast overview map can be created with a reasonable accuracy which is related to the camera resolution, however for a scientific investigation a smaller camera-to-object distance and orthogonal viewing angles are inevitable. These requirements can only be fulfilled with a manual operation of the drone using today's state-of-the-art methods. It can be seen that the industry is heading into the direction of fully autonomous drones with intelligent object avoidance as produced by the Leica Geosystems with the *BLK2FLY*[11]. However, these drones still have to prove their usability in real live use cases.

Regarding the laser scan, the size of the point cloud raw data can be overwhelming and is a major issue in projects today. The storage can be reduced by producing a 3D mesh out of the raw data, however this has a smoothing effect on the data set and therefore results in a loss in accuracy. Also, the texturing remains an inherent problem. Although modern scanners use HDR images or a mounted SLR camera for the colourization of the point cloud, the viewing angles limited to the setup points, strong variation of the lighting conditions while instrument turning and limited colour correction possibilities in the processing software lead to an unsatisfying texture result.

[10] https://threejs.org/

[11] Leica Geosystems: https://leica-geosystems.com/de-at/products/laser-scanners/autonomous-reality-capture/blk2fly

In general, scanning only for the purpose of scanning leads to an enormous amount of unused data. It is crucial to derive the required information out of the data set as soon as possible because the data may be unavailable in the near future by the rapid change in technologies, software products and data formats if it is not updated and stored properly.

Summary

Every use case demands an individual surveying solution because every surveying technology has advantages and disadvantages. It is the task of the surveying expert to choose the right technology for the given task and to possibly combine technologies in order to overcome the limitations of a single approach.

To obtain an optimal result in future surveys, terrestrial photogrammetry, drone-based photogrammetry and laser scanning have to be combined to a single output. In the demonstrated workflow, using the software programmes Agisoft Metashape and Cyclone 3DR, the geometry information of the mesh was extracted from the laser scanner data only. The combined processing of terrestrial images and drone-based images in Agisoft Metashape would lead to an omnidirectional texture which can be mapped onto the laser scan mesh after the import into the software. The combined result incorporates the benefits out of all approaches. Nevertheless, the combined processing of data sets with different qualities (terrestrial images and drone-based images) in a single adjustment can lead to a lower 3D accuracy of a derived photogrammetric mesh. This can be neglected in this demonstrated workflow because only the resulting texture is extracted.

In some cases, a drone survey may be the only feasible option, if the object of interest is in a remote area. On the other hand, only terrestrial photogrammetry can be applied in a designated no-fly zone. If the lighting conditions are bad (e.g. caves) only terrestrial laser scanning can be applied. In each case, the insufficiencies of a single technology have to be clearly communicated with the contractor or documented alongside with the measurement data to provide the quality information for future users. This avoids mistreatment of the data sets for instance if an archaeologist wants to perform detailed brickwork investigation on the basis of an insufficient laser scan texture or in the worst case scenario sloppy photogrammetric models are used for structural investigations and monitoring.

Also, the target group of the survey data has a big influence on the output because this defines the outcome and the publishing format. Although a survey is a product for its own, it is always part of bigger workflow and there must be a life beyond the visualisation of point clouds in cultural heritage. Its use for historic reconstruction, structural investigations or as a planning foundation for renovation work has to be a key element for the planning of the project. Due to the enormous amount of raw data, the required expert knowledge for handling and the rapid change in technology the acquired data sets have to be processed and stored according to their initial purpose right away and must be easily accessible to the target group. Unprocessed raw data for documentation purposes that is not updated and processed will become unavailable already after a few years.

At the example of Neu-Wildon, the restoration company has been provided with the 2D rectified and orthographic overview image and the 2D rectified wall plans which can be opened easily with a custom PDF viewer. The point cloud dataset will be stored in ASCII format (.asc) for future structural monitoring by TU Graz and the castle owner, alongside with the high resolution terrestrial photogrammetric model in OBJ format which can also be opened by the default Windows viewer as well as professional software. The reconstruction will be made available with an online viewer to be presented to a wider public with access to the internet.

Conflicts of Interest Disclosure

No potential competing interests have been reported by the authors.

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