Needs for Documenting and Modelling Cultural Heritage Objects

Conservation of culture heritage objects is complex and multidisciplinary activity. The mission of conservation is to retain and protect valuable historic objects, architecture or places as they exist. One of the key activities in conservation management of immovable cultural heritage is recording (Lettelier, 2007). Recording is the capturing of graphic and photographic information, which describe the physical configuration, condition and use of heritage object of place. Recording also means the acquisition of new information deriving from different activities on the object. Documentation is a broader term, meaning systematic collection and archiving of records in order to preserve them for the future reference (Lettelier, 2007).

The foundations of international and systematic approach to the conservation and restoration of monuments and sites in the 20th century have been set in the Athens Charter from 1931 and in the Venice Charter from 1964. The latter consists of a set of guidelines adopted by architects and technicians of historic monuments at their 2nd International Congress in Venice (The Venice Charter, 1964). The importance of documentation is emphasised in the following sentence from the 16th Article: “In all works of preservation, restoration or excavation, there should always be precise documentation in the form of analytical and critical reports, illustrated with drawings and photographs.” Although this charter is nowadays regarded only as a historic document, it is considered as the most influential document on conservation.

International Council on Monuments and Sites (ICOMOS) has ratified the Principles for the Recording of Monuments, Groups of Building and Sites (ICOMOS, 1996) in 1996, which are the current framework and guidelines, defining the reasons, responsibility and planning for recording, as well as the content, management, dissemination and sharing of records.
Recording and the scope of documentation depends on many factors and the available resources (finances, tools, time) are limited as well. However, the produced documentation should satisfy at least the following requirements: long-term value, possibility of upgrade, and user-friendliness. The recording and production of technical documentation on cultural heritage objects may depend on the current state of the object, maintenance of the object (inspection of critical parts, restoration, and reconstruction), etc. However, documentation can serve only to record the current state of the object or to use the virtual reality modelling and augmented reality tools to attract the broader community (tourist visits, education on the historical development, etc.).

The essential technical requirements for architectural and close-range photogrammetry were already developed in the 19th century (Luhmann et al., 2014). Stereophotogrammetry, classical geodetic methods and simple measuring tools were mainly used in the first half of the 20th century. In the last decades, many new technologies and tools became available for recording and documenting the cultural heritage objects (Stylianidis et al., 2016). The geometric documentation of a monument is more versatile, richer and complex, consisting of products such as vector drawings, raster images, 3D models, animations etc. Documentation can be produced at different scales and accuracies, depending on the extent and complexity of the object, as well as the requirements from the conservation experts (example on Figure 1). Those requirements need to be carefully predefined, both in accuracy and detainees and also in expected final products. According to that, the surveying and photogrammetric procedures and techniques can provide reliable and accurate geometry, shape, and position of objects in selected coordinate system, metric images, consistent and topologically correct 3D models and plans, detailed topography of the building surroundings, landscapes, etc.
Figure 1. Example of documentation of a cultural heritage object (Source: Geodetski inštitut Slovenije, 2001)

However, there are also limitations of available technologies. Cultural heritage objects are often very complex, having complicated base plan of irregular shapes. Exterior of the building may be in the form of geometrically irregular shapes, circular shapes, roofs of different heights, balconies, towers, etc. The complete capture of such complex geometry requires recording from a large number of standpoints, and the recorded images or point clouds have to be properly registered. Registration is possible with the accurate geodetic measurement of the instrument positions or by using ground control points (GCPs). In case of the tacheometry, stations have to be either directly visible to each other or they need to have an open sky view in the case of GNSS surveying. Cultural heritage objects often lie in remote, hardly accessible terrain, e.g. above steep walls such is the example of the object in Figure 2, in narrow valleys, in overgrown areas, between water surfaces, or in densely populated urban areas. The use of geodetic measurement methods can be more demanded in these cases. The additional problem is signalization of the GCPs on the object surface, due to the restrictions on access to the object or condition of the structure (risk of collapse).

Significant obstacle in surveying can be also caused by visitors, as cultural heritage objects are often highly visited and attractive tourist destinations (Figure 2). The
captured images of the building should be without hidden spots, visitors or other disturbing objects as much as possible. Many data acquisition techniques require good lighting conditions, which is in the middle of the day and in the nice weather, when the crowd of visitors is at the most. However, their access to the attractions due to the need for surveying usually cannot be limited.

Figure 2. Crowdedness and unfavorable position of important cultural heritage object for surveying (https://www.thelocal.de/20170213/more-tourists-than-ever-before-travelling-to-bavaria-figures-show)

The main aim of this paper is to present and discuss the potentials of modern surveying technologies and tools for recording, documenting, geometric modelling and visualisation of cultural heritage objects. It is important to understand the basic principles, surveying conditions and possible limitations of these techniques in order to select the best approach in the practice. This topic is discussed in more detail in the following chapters.
Available technologies

Different methods and technologies can be used in different phases of documenting cultural heritage objects. Establishment of the basic surveying network is indispensable if we want to incorporate the object model into surroundings data and it is strongly recommended, when the size of the object requires data acquisition from different standpoints. GNSS survey and/or tacheometry can be used for measuring selected number of well-defined GCPs. The tacheometry can also be used for measuring the object dimensions, but terrestrial laser scanning, terrestrial or unmanned aerial vehicle (UAV) photogrammetric survey can fulfil this task as well. The last two mentioned technologies are used for capturing the images of the object.

**GNSS surveying**

Global Navigation Satellite System (GNSS) is a positioning technology that provides global coordinates which can be transformed into selected reference coordinate system. Accurate positions of the rover GNSS receiver can be achieved using observation data from the near-by base GNSS receiver. The positions can be taken in real time or in the post-processing. From our experience, the accuracy of the real-time acquired positions is around 5 cm and on the cm-level in the post-processing. An example of GNSS surveying of a GCP is shown in Figure 3.
The positives of the GNSS technology are fast acquisition for the real-time surveys, instant positioning in the selected coordinate system and independent measurements of surveyed points – they don’t need to be visible from the adjacent points. GNSS surveying is very suitable for the GCPs positioning if a few centimetre accuracy is acceptable. The main disadvantage, however, is limitation in the areas where obstacles, like dense vegetation, relief obstacles or build structures omit open sky direction to minimum number of adequately distributed satellites. In such cases, measurements are often not possible at all or can provide lower accuracy results. In areas with no GNSS permanent station network, the demand for the base GNSS receiver needs to be considered.

Tacheometry

The tacheometric survey allows determination of the 3D point positions. The horizontal angle, the vertical angle and the distance are measured for each point. The measured points are signalized with a prism in the precise measurement. The reflective tape or other markers can be used for measuring detail points. Modern total stations enable measurements without special reflectors. Precise instrumentation and an appropriately selected surveying method allow the millimeter precision of the 3D point position.

In the procedures for the cultural heritage documentation, the tacheometry is the most often used technology for the establishment of a surveying network (Figure 4) and measurement of the GCPs, check points and detail points (Agnello and Brutto, 2007; Andaroodi and Taqipour, 2012; Barsanti et al, 2013; Canciani et al, 2016).
The main advantages of tacheometry are high precision of measurements and the possibility of surveying individual points, which is especially useful for the production of wireframes (significant objects and contour lines). The method is indispensable for indoor and underground surveys, as well as for the georeferencing of data using various technologies, e.g. terrestrial laser scanning, UAV and terrestrial photogrammetry. The main limitation is, however, need for the direct visibility between the standpoint and the measured point.

Terrestrial laser scanning (TLS)

Terrestrial laser scanners are active sensors for mass remote survey. The laser beam measures the distance to every obstacle that it hits. It can measure many points in a short time, even up to two millions points per second. The result of a scan is a point cloud. Point clouds from different scanner standpoints can be merged together using registered artificial targets or with surface matching methods. Georeferencing of a point cloud can be carried out directly with an orientation to the points of the surveying network or indirectly through GCPs (Vosselman and Maas, 2010). Most terrestrial laser scanners support image collecting for a better and easier interpretation of the data (Figure 5). Laser scanning technology is commonly integrated in modern total stations.
The main advantage of using terrestrial laser scanning is a high quality 3D surface acquisition. The disadvantages of this technology are different spatial resolution of the point clouds according to the distances of the points from the scanner, scanning only the areas in the scanner’s field view, and the large amount of data which implies to be reduced for further processing. In most cultural heritage documentation cases, the combination of terrestrial laser scanning with other methods may be the best solution (Grussenmeyer et al., 2008).

**Terrestrial photogrammetric survey**

Terrestrial photogrammetric survey of an object is based on images, taken from a camera station from the ground. In traditional photogrammetry, a stereoscopic method is most often used. In the normal case, both optical camera axes are normal to the base (the base is the straight line between the two perspective centres) and parallel to each other (Kraus, 2007). It is a requirement of stereophotogrammetry that every point of an object appears in at least two photographs (Figure 6). In the practice, an overlap of 60-70 % between the two images is used, while the theoretical minimum is 50 %. The stereo-images should be taken around the object.
Figure 6. Terrestrial photogrammetric survey stereo pair images.

Photogrammetry is used above all for the reconstruction of three-dimensional objects from images. Weather conditions while taking photographs are important, in ideal case illumination of the entire object should be equal, any huge differences between shaded and illuminated parts should be avoided. If a building is tall, it can be difficult to photograph its higher parts, especially where the surroundings is not obstacle free. Nowadays, a photogrammetric survey with a UAV can be a good solution in such cases.

**UAV photogrammetry**

UAV (Unmanned Aerial Vehicle) is a generic aircraft design to operate with no human pilot onboard. In combination with the ground control station, it forms an unmanned aerial system (UAS). UAV can be equipped with photogrammetric measurement system, including still-video or video camera, thermal or infrared camera system, airborne LiDAR system, or a combination thereof (Eisenbeiss, 2009). Small or medium size cameras are most commonly used with UAVs. Images from a UAV can be taken remotely from the flight controller or automatically in a pre-planned mission. A grid-mission is used for recording vertical images and a circle-mission is used for taking
Figure 7. UAVs (left) and planning a mission (right).

As noticed before, the UAV photogrammetry can be combined with the terrestrial photogrammetric survey. Similar to the terrestrial photogrammetric survey, the images from UAV need to overlap in order to calculate 3D coordinates. The main advantages of using the UAV are possibilities of taking images from the air and from the sides, which are not accessible from the ground, and a lot of images can be taken in very short time. Disadvantages are relatively short UAV battery autonomy, usually up to 20 minutes, which can be solved with combination of more short missions with battery replacement between them. UAV can’t fly in rain, in strong wind and also in freezing cold days. Area of flying should be obstacle free, in some areas UAV flying is restricted or even forbidden.

Technologies for creating the model
The computer vision community introduced an approach for creating point clouds from overlapping images, taken from the UAVs and from the ground, known as Structure from Motion (SfM). In SfM, features are obtained from images using feature detectors. Corresponding features are then matched according to their descriptors. In the next step,
a sparse bundle adjustment is performed in order to simultaneously estimate the interior and exterior orientation of the camera and transform the image coordinates of corresponding features into 3D coordinates to produce a sparse point cloud. The sparse point cloud is then intensified into a dense point cloud using dense image-matching algorithms (Micheletti et al., 2015). In the absence of control information, SfM-based point clouds are usually referred to an arbitrary reference frame (He and Habib, 2016). The transformation of the point cloud in the reference coordinate system can be achieved by the use of the GCPs. These must be included as constraints in bundle adjustment rather than by just applying 3D similarity transformation from an arbitrary reference system after SfM (Benassi et al., 2017). If the reference coordinate system is not required for the project, at least 2 actual distances in different planes are required in order to set the correct scale of the model.

Geometrically, SfM-based point clouds are comparable to the point clouds obtained with TLS. A point cloud can consist of several hundred millions of points. Besides the points of surveyed objects there are many other points of vegetation, people and other objects. With classification of points, which can be partly automated and partly manual, all those points should be filtered. To create a 3D model from the point cloud, a triangulated irregular network (TIN) is calculated from the points. The resulting mesh can then be textured from the input images. The 3D model can be finally exported as a digital 3D model, can be printed or being used in VR or AR. The SfM procedure of a photogrammetric survey of a building is shown in Figure 8.
Technologies for presentations

When a 3D model of an object is generated, there are several ways of its’ visualizations and presentations. A basic visualization is a digital 3D model. The 3D model can be exported in a file or uploaded to a web platform, e.g. Sketchfab. A user can zoom-in or zoom-out of the object, can rotate around it or pan it.

A virtual fly-around is a video animation of a virtual fly around the object. Using special software, a fly-path is selected or drawn and then the height, orientation and angle of the virtual camera are selected.

Virtual reality (VR) is a computer simulated environment where users usually wear VR headsets which project the digital data in front of the eyes.

A 3D print is a physical representation of a 3D model. 3D printers use high temperature nozzles to melt special plastic filaments to build layers upon layers to create a physical 3D model. A 3D print can be made in a single colour, in two colours or in full colour.

Augmented Reality (AR) is a live view of a real-world environment where elements are augmented by computer-generated information. In the case of a cultural heritage object, an AR view can be produced by a tablet or a smartphone over printed floorplan or the
orthophoto image of the object. The AR view can incorporate a full-colour 3D model of the object. An AR view can also be generated over a 3D print.

Some of the above mentioned visualizations are presented in the next chapter.

Creation of 3D models of selected cultural heritage objects

Procedures and results are presented at selected cultural heritage objects in Slovenia: Chapel on Krvavec, Smlednik castle, Brestanica castle, and Ljubljana castle. Selection based on objects’ differences according to complexity and expected final products. In each case a selection of used technologies and methods leads to results of the requested quality.

Chapel on Krvavec

The chapel on Krvavec was built by the plans of the famous architect Jože Plečnik and was opened for public in 1929. It is set 1700 m above sea level in what is now Krvavec ski resort (Zupnija Cerkle, 2019). In snow-less period it lies in the pasture area and is easily accessed from all sides. Rectangular shaped object with simple roof shape has a kind of a canopy at the front of the entry. Therefore it can be taken as a relatively simple object, rather small, without many issues at surveying. The expected final results were only basic: a point cloud and a printed 3D model.
Initially, five GCPs were surveyed for the modelling purposes of the chapel and placing the model into the national coordinate system. Both GNSS and tacheometry were used, GNSS for defining absolute coordinates of GCPs in selected coordinate system and tacheometry for more accurate geometric relations between them. The vertical images were taken automatically in a UAV pre-planned mission and the oblique images were shot manually with a UAV at two different heights. Additional images were taken from the ground (Figure 9). The acquired images and GCPs coordinates were then processed in an SfM software. The results were a digital 3D model and a 3D print (Figure 10). Images of the object were taken from 20 – 30 m, meaning the resolution of the resulting mesh is around 1 cm. The actual accuracy hasn’t been determined but since the precision of the GCPs was below 1 cm, the expected accuracy is on a cm-level.

Figure 10. Image of the chapel on Krvavec, its’ 3D model and 3D print.

**Smlednik castle**

Smlednik castle is a medieval castle on a hill above the town of Smlednik, north of
Ljubljana. It is supposed to be initially built in the early 12th century, but later several additions and renovations were made. Nowadays only the ruins of the castle remain above the steep 20 – 30 m high rocks (Wikipedia, 2019). The object is much larger than the chapel in the first case. The castle is situated on the steep rock which limits the possibility of taking images from the ground. Because of the ruins, some extra caution should be taken while placing GCPs in such cases. Besides a digital and a physical 3D models, the expected results also included AR presentations.

Figure 11. Image of Smlednik castle, images distribution, point cloud and TIN model, 3D model – oblique and vertical view.

For the modelling purposes, 6 GCPs were surveyed by GNSS. Due to problematic access around the object and huge high differences, tacheometry was not performed. GNSS survey resulted in GPCs’ precision of under 1 cm, which was sufficient for further modelling. 244 manually triggered images were taken by a UAV. The final results of the SfM processing were a digital 3D model, a 3D print and an AR model, created in Vuforia gaming software. A video animation of a virtual rotating around the castle was also generated. Some of the captured images and the final results are presented in Figures 11 and 12.
Brestanica castle

Officially named Rajhenburg castle by the former German name of the town, the castle was built in the early 12\textsuperscript{th} century on a hill above river Sava. It has a vivid history, from the Ministerialis to the Trappists’ monastery; it also served as the eviction camp in the World War II. It has belonged to the local municipality from 2004 and was being renovated from 2010 to 2012 (Grad Rajhenburg, 2019). The castle rises from a steep forested hill and is accessible only from the north-west side (Figure 13a). The ground dimensions of the castle are approx. 54 m × 42 m and the height is around 20 m from the base and 28 m from the lowest ground point.

To create a model of the castle, 6 GCPs were located around the castle. The locations can be seen in Figure 13b. The GCPs were surveyed by GNSS, however one of the GCPs had a bad accuracy because of the thick vegetation and castle walls in the vicinity of the point. The point was excluded from further data processing. The precision of the other GCPs was around 2 cm.

Similar to the previous cases, the imagery was a combination of vertical UAV images from a pre-planned mission (Figure 13c) and oblique images, taken manually around the
castle at two different heights. Around 30 images on a circle around the object were taken at each height.

![Figure 13. Brestanica castle photo (a - above), distribution of GCPs in vertical view (b - right), distribution of UAV imagery (c - below).](image)

Some images were also taken from the ground. Due to bad overlap of the ground images, SfM was not able to correctly match ground and UAV images. Only UAV images were used to calculate dense point cloud. The final results of the SfM processing are a digital 3D model, a 3D print and an AR visualization (Figure 14). The AR visualization works on the floor plan, on the orthophoto image and on the 3D print.

![Figure 14. Digital 3D model and 3D print of Brestanica castle.](image)
Similar to other presented cases, the resolution of the resulting mesh is approx. 1 cm and the expected accuracy of a point in the point cloud is on a cm-level.

A digital model of the castle was also created in SketchUp using measurements from the 3D model derived from the SfM point cloud. The SketchUp model was exported and fitted to the surroundings in Google Earth, as can be seen in an image in Figure 15.

![Figure 15. 3D vector model, Brestanica castle model fitted into Google Earth.](https://example.com/figure15)

**Ljubljana Castle**

Ljubljana Castle was originally a mighty medieval fortress, located on a castle hill above downtown Ljubljana, the capital of Slovenia. It was probably built in the 11th century. It was rebuilt several times in the 2nd millennium and its present shape is rather complex (Figure 16 left). Recently, it has been used as a major place for cultural and historic events (Ljubljana Castle, 2019).

![Figure 16. Ljubljana castle (https://www.ljubljana.si/sl/mestna-obcina), TLS point cloud of part of the castle.](https://example.com/figure16)

The castle is quite large, but the project goal was to create an exact 3D model of the part of the castle only. The absolute positions of the four surveying network points were
determined with RTK GNSS method. These points were used for the georeferencing of all surveyed data. The entire surveying network, which includes 10 points, was stabilized around the castle and it defined the coordinate basis for the GCPs’ measurements. The results of the terrestrial laser scanning of a chapel and a part of the facade in the castle yard are presented. The Leica BLK360 was used with the highest possible resolution of the scanner, namely 5 mm / 10 m. The area of interest was scanned from three standpoints and resulted in a point cloud (Figure 16 right). The acquired data allows the determination of precise and accurate dimensions of the object, as seen from the Figure 17.

The final results are topologically correct plans of facade, a digital 3D model, a 3D print, and shading analyses (Figure 17).

**Discussion**

The article presents four different examples of cultural heritage object modelling in Slovenia, from relatively simple one in the easy-to-access area to more complex objects, positioned on hills, where access and use of measuring technics were limited. Luckily,
none of these objects is so popular that tourists and other people would make additional limitations at the terrain survey. We defined absolute coordinates of the model in the national coordinate system in all cases, thus allowing us to combine the model to any other spatial data and to create many attractive visualizations of the object in the surroundings.

Tacheometry and GNSS surveying are the basic geodetic positioning methods and both are very suitable for the establishment of a coordinate reference. Tacheometric surveyed points can be determined with a mm-level accuracy, but there are limitations of visibility between points and it usually includes several standpoints. The great advantage of a tacheometric survey is the use of reflectorless mode, but the method can still be time consuming. RTK GNSS surveying method offers a cm-level accurate positions in a few second visit on a surveyed point. However, the actual accuracy, especially in the vertical component, can decline to beyond 10 cm. Therefore, it is advisable to perform repeat surveys on the same points. Of course, the best solution is the combination of both techniques.

Overlapping images or laser scanning can be used to remotely gather data for construction of a 3D model of an object. Images can be taken from the ground or from the air using UAV. Terrestrial photogrammetric survey is very limited, especially for large, tall and complex buildings. The solution lies in the form of UAVs. Eventually, UAVs can be taken to any point in the air. However, there are limitations to where they are allowed to fly and there is a concern of safety. Additionally, UAVs are limited in image sensors. Smaller UAVs have only a built-in camera option which is limited in size and quality. Most of the medium size UAV can take different cameras on board, but usually only compact cameras. Only large and very expensive UAVs can fly with DSLR-class cameras.
TLS is a very efficient technology, recording a large number of points in a very short time. If a TLS standpoint is near the object, the density and the accuracy of measured points is also very high. When using TLS, one has to be aware of the blind spots. If the TLS is used to capture a building, there are similar limitations as in the terrestrial photogrammetric survey: tall objects, hardly accessible parts of the building, etc. Again, UAVs could overcome such limitations.

It is obvious, that only combination of different technologies and methods with accuracy estimation of each methodology and quality estimation of the final product (model) enabled various final outputs and products: correct models for authorities, investors and maintenance as well as attractive presentations for public.

In all, the presented technologies can provide a very accurate, high level of detail 3D models or meshes of an object or any part of the object. Even if a high accuracy is required, the right distribution of GCPs, measured with a precise total station, and close range photogrammetry or TLS can fulfil the task.

Finally, only geometrically correct and detailed models of cultural heritage object are the guarantee for long time preservation and documentation.

References:


https://www.gradrajhenburg.si/


https://www.ljubljanskigrad.si/


https://sl.wikipedia.org/wiki/Grad_Smlednik