Use of LIDAR Data in the 3D/4D Analyses of the Krakow Fortress Objects

Ewa Glowienka 1, Krystyna Michalowska 2, Piotr Opalinski 3, Beata Hejmanowska 4, Slawomir Mikrut 4, Piotr Kramarczyk 4

1 Kielce University of Technology, Kielce, Poland
2 University of Agriculture in Krakow, Krakow, Poland
3 Historical Museum of the City of Krakow, Krakow, Poland
4 AGH University of Science and Technology, Krakow, Poland
eglowienka@tu.kielce.pl

Abstract. The article presents partial results of studies within the framework of the international project "Cultural Heritage Through Time" (CHT2). The subject of the study were forts of the Krakow Fortress, which had been built by the Austrians between 1849-1914 in order to provide defence against the Russians. Research works were aimed at identifying architectural changes occurring in different time periods in relation to selected objects of the Krakow Fortress. For the analysis, the following LIDAR (Light Detection and Ranging) data was applied: Digital Terrain Models (DTM), Digital Surface Model (DSM), as well as the cartographic data: maps and orthophotomaps. All spatial data was obtained from the Polish Main Office of Geodesy and Cartography (Główny Urząd Geodezji i Kartografii - GUGIK). The majority of the cartographic data is available in the form of Web Map Services (WMS) on Geoportal (www.geoportal.gov.pl). The archival data was made available by the Historical Museum of the City of Krakow, or obtained from private collections. In order to conduct a thorough analysis of objects of the Krakow fortress, DTM and DSM data was obtained, either in ASCII format, or in the source *.las (LIDAR) format. On the basis of DTM and DSM, the degree of destruction of selected fortress objects was determined, occurring as a result of the action of demolishing those objects in the interwar period (1920-1939) and in the 1950s. The research has been made on the basis of all available cartographic materials, both archival (plans, maps, photos) and current (topographic map, orthophotomap, etc.) ones. Verification of archival maps and plans was carried out by comparing current digital images of the existing forms of fortifications with designs developed by the Austrians. As a result, it was possible to identify the differences between the original design, and the current state of the objects concerned. The analyses, which have been conducted, also allowed checking the legitimacy of locating the forts in terms of the object visibility from the enemy's side (foreground), presence and number of "dead fields" in the foreground, the effectiveness of blurring characteristic military forms by means of masks formed from tree rows and shrubs. Furthermore, the analyses involved examination of the impact of erosion resulting from the natural process of silting drains of forts' ground forms, as well as processes of obliterating of the slopes, sliding of the scarps, and flooding of moats and caponieres.
1. Introduction

In the second half of the 19th century the construction of fortifications was evolving under the influence of an extremely quick development of battle systems and techniques. At that time, one could identify two diametrically different epochs in the Austrian fortification school. The first one is the epoch of polygonal works, lasting from the 1820s until the late 1860s. The second epoch is a period falling on the end of the 19th century and the beginnings of the 20th century, marked by artillery forts. Fortifications covered by this paper have been constructed just in that period. The subject of the study are forts of the Krakow Fortress, which were built by the Austrians between 1849 and 1914 in order to provide defence against the Russians. The works described herein constitute one of the stages of the international "Cultural Heritage Through Time" (CHT2) project [1], implemented within the framework of Joint Programming Initiative in Cultural Heritage” JPI-CH [2] by a consortium composed of 4 scientific research teams, representing: Italy, United Kingdom, Spain, and Poland.

The goal of the project is to develop a 3D/ 4D database, composed of cultural heritage objects that belong to the remains of the still existing or destroyed defence forms, located in various parts of Europe. They include the following: Hadrian's Wall (UK) [3], the city centre of Milan (Italy) [4], medieval towers of Avila (Spain) [5], and the Fortress of Krakow (Poland) [6]. Each of those objects has a different history, and is in a different state of preservation of its former magnificence and defence functions. The 4D database is being created on the basis of archival materials (old plans, maps, drawings, descriptions, pictures, photos, etc.) and current data, mainly originating from photogrammetric measurements and laser scanning measurements (terrestrial and aerial). The additional objective of CHT2 is to publish the database and make it available on the Internet, with a possibility of performing 4D GIS analyses, e.g. tracking how a given object has been changing over time, what has been destroyed by man's activities, and what destructions are due to natural reasons, like floods, earthquakes, environmental pollution, etc. [7 - 13].

The article presents partial results of studies within the framework of the international project "Cultural Heritage Through Time" (CHT2). Research works were aimed at identifying architectural changes occurring in different time periods in relation to selected objects of the Krakow Fortress.

2. Study Area

The Krakow Fortress is a complex of about 50 defence structures of the fort type, located in the centre of the city of Krakow, and on its outskirts. The city centre constitutes the core of the fortress, supported by three rings of defence fortifications around the city.

![Figure 1. Location of analysed fortress - Krakow (Poland)](image)
and scenic (a vantage point) values. Since regeneration of the demolished west bastion front has been scheduled (relics of that front are buried in the moats), it is important to record the current condition of the object, and to prepare a detailed documentation on the basis of photogrammetric and laser scanning measurements [11, 12]. The data set obtained will provide a basis for 3D modelling and will enable, among other things, determining the depth of secondary infills.

Another object under the project is Fort no. 47 Lysa Gora, which is a unique monument, and one of the first forts of the ring fortress. Together with the armoured Fort no. 47a Wegrzce, it formed a fortified complex on the most important operation line blocking the Warsaw route. The fortified complex was being built over years, and supplemented with supporting elements: roads, plant masks, entrenchments, batteries and ammunition bunkers. In the last phase before World War I, a bunker for heavy machine guns was added, a prototype for battle bunkers typical already for fortifications of the 1920s and the 1930s. Later the Polish army used Fort Lysa Gora, yet the Fort was damaged only to a minor extent – its moats have partly been filled in. The object is gradually being revitalized. The fortress landscape is endangered with an aggressively encroaching suburban development. Precise LIDAR measurements make it possible to record the present day condition of the fort, which may be helpful during reconstruction works.

The smallest object is Fort no. 47½ Sudol, which is an armoured structure of a non-standard construction. In the middle of the 20th century it was destroyed (blown up and demolished). Its current condition renders understanding of the monument's function and form impossible. The photogrammetric documentation and scanning will facilitate works relative to digital reconstruction (3D model), and verification of archival documentation.

Figure 2. The visualization of 3D models obtained from LiDAR data for selected forts: a) Kosciuszko, b) Lysa Gora, c) Sudol

3. Data and Methods

For the analysis, LIDAR data was used: Digital Terrain Models (DTM), Digital Surface Models (DSM), and the cartographic data: maps, orthophotomaps. All the spatial data was obtained from the Polish Main Office of Geodesy and Cartography (Główny Urząd Geodezji i Kartografii GUGIK). Most of the cartographic data is available in the form of Web Map Services (WMS) on Geoportal (www.geoportal.gov.pl). Archival data were made available by the Historical Museum of the City of Krakow or from private collections. In order to conduct a thorough analysis of objects of the Krakow fortress, DTM and DSM data was obtained, either in ASCII format, or in the source *.las (LIDAR) format. Additionally, in years 2016 and 2017 new records of Terrestrial Laser Scanning (TLS) were obtained using 3D Laser scanner (Faro Focus 3D) [13 - 18].

On the basis of DTM and the DSM, the degree of destruction of selected fortress objects was determined, occurring as a result of the action of demolishing those objects in the interwar period (1920-1939) and in the 1950s. The research has been made on the basis of all available cartographic materials, both archival (plans, maps, photos) and current (topographic maps, orthophotomaps, etc.) ones. Verification of archival maps and plans was carried out by comparing current digital images of the existing forms of fortifications with designs developed by the Austrians [12, 19 - 22].
The altitude data in the *.las format was read and processed by means of the TerraScan software, while the ASCII data was processed using an open source SAGA software (Figure 4-8). Using the Autodesk 3Ds max software, transverse and longitudinal profiles were generated, which were later collated with profiles available in archival plans of the fortress. The digital terrain model, obtained by means of aerial laser scanning (LIDAR), was compared with archival plans of the fortress objects, contemporary topographic maps, and with an aerial orthophotomap.

![Figure 3](image.png)

**Figure 3.** Example for the result of Terrestrial laser scanning (TLS) for destroyed part of Fort Kosciuszko - on left, 3D model of the Fort Kosciuszko obtained from LiDAR data with marked (in red) existing parts and (in green) destroyed parts measured with TLS - on right

Based on comparison of the archival data with the current data, information has been obtained on the following issues:

- differences between original designs and actual implementation of them, and the existence of errors in historic documentation,
- the effect of the flow of time, the impact of natural factors,
- the present-day condition of the examined objects, the scope of demolitions completed to date, and spatial deformations caused by municipal construction projects.

### 4. Results and analysis

As a result, it was possible to identify differences between the original designs, and the current state of the objects concerned. The analyses, which have been conducted, also allowed checking the legitimacy of locating the forts in terms of the object visibility from the enemy's side (foreground), presence and number of "dead fields" in the foreground, the effectiveness of blurring characteristic military forms by means of masks formed from tree rows and shrubs.

#### 4.1. Fort no. 2 Kosciuszko

Based on archival Austrian plans from 1902-1914, a 3D model of the Fort was made in CAD environment. Data from terrestrial laser scanning provided a basis for generating a current, 3D model of the object. Following the analysis of both 3D models, it was possible to identify substantial divergences between the condition of the Fort in the beginning of the 20th century, and its present-day state. When examining the laser scanning model one can notice that the bend between the masonry wall linking the demolished bastion I and the caponiere is smaller by 10 degrees than as shown in the historic documentation. Based on the analysis of documentation from the 1850s, that is from the period of construction of the fort, and based on the current 3D model, the correct route of the south curtain wall was identified. Symmetry of the whole structure projection in relation to the east-west axis going through the centrally located mound was noticed. The north curtain wall has its layout adjusted to the steep edge of the hill, while the south one, due to the smaller land inclination, could be shaped more freely (Figure 4). As the contemporary LIDAR measurement has proved, also the south curtain wall has the nature
similar to that of the north one. Another difference is that of the size of caponieres IV and V. In documentation from 1914, those elements are evidently smaller than as demonstrated by results of contemporary measurements. As regards those elements, the earlier plans from the 1850s and the 1860s turned to be made correctly. However, other elements were changed in the course of construction, e.g. the shape of cofferdam closures protecting the internal courtyard of neck barracks, or the form of Chapel of Blessed Bronislawa. Changes of that type may suggest the possibility of introducing corrections in the course of construction of the south curtain wall or corrections to the caponiere size. The error in the Austrian plans from the beginning of the 20th century was also repeated in the Polish copy of the design that was attached to the survey documentation of the former Krakow Fortress from 1927. One must add that incorrect data concerning the Fort Kosciuszko could also be seen on the map of the Krakow Fortress (scales 1:10.000 and 1:25.000), which was used and updated in the years 1901-1914. One can speculate that divergences between the today's condition of the object and that recorded in the Austrian military engineering documentation may result partly from an accidental action, and partly from a deliberate action undertook for some strategic reasons.

Following the impact of natural and anthropogenic factors (partial demolitions in the 1950s), earth embankments in the east and in the south sides were levelled. The uncontrolled growth of trees and bushes causes successive masking of certain parts of the object, and a more and more difficult access to it. Based on the analysis of results of laser scanning measurements it was possible to identify shapes and limits of particular arable fields, former vast agricultural areas (presently afforested), located in the west and east sides of the Fort.

Based on the analysis of digital model of land coverage and after the removal of a high vegetation layer, a complete destruction of bastion I with its main access gate, a substantial destruction of bastion II, and a partial destruction of bastion III were noticed (Figure 6). At the same time high level of moat backfills shows the likelihood of existence of bottom parts of masonry slopes of those bastions at the depth of up to 6 metres below the ground level. It is highly probable that there exist foundations of caponiere no. VI and caponiere no. VII (Figure 3, Figure 4a, Figure 5).

![Figure 4](image-url)

**Figure 4.** Fort Kosciuszko: a) determining the current outline of the fort on the basis of LIDAR data, b) the current outline of the fort and lines of profiles (A-A', B-B') imposed on the archive plan.
Figure 5. Kosciuszko fortress profiles (A-A', B-B') showing changes between archival plans and the current state.

a)  b)

Figure 6. The 3D visualization of the fortress Kosciuszko area, prepared on the basis of LIDAR data and a 3D model derived from archival plans: a) complete object reproduced from Austrian documentation b) currently existing fragments of buildings - lack of the bastions no. I, II and the caponieres no. VI, VII.

The legible contour on the 3D model of the west front backslope includes a visible, even today, beginning section of a hidden link with field entrenchment no. 2 ½, which once used to exist in the foreground. Moreover, in the south part one can see the former fortress road, fragmentarily overlapping with the present-day highroad. In the east, in front of the barracks, a ground and masonry terrace is visible, which has existed in documents from before World War II. The vantage point created in that area was built as a secondary structure, probably of demolition materials obtained in the 1950s.

4.2. Fort no. 47 ½ Sudol
Based on the analysis of plan of Fort Sudol from 1897 and of laser scanning model, conformity of overlapping of plot border lines, as well as quite considerable divergences were identified, namely the Fort layout deviated by 5 degrees from the Fort plot outline, and from the road towards the village of
Batowice. Moreover, the block of the barracks was asymmetrically shifted towards the left shoulder of the Fort by ca. 6 m (Figure 7).

The company conducting demolition works destroyed the block of the barracks in 80%. On scanned images one can see the relic of a concrete battery annexe with a nest for one of the armoured towers. The north corner of the fortress land plot has been cut by the railway line, which was run in a deep excavation passing through the hill, on which Fort Sudol has been built.

![Figure 7](image)

**Figure 7.** Fort Sudol: a) 3D model of LIDAR data, b) 3D model of archival data, c) the profile along A-A line marked on a, b, showing changes between archival plans and the current state

### 4.3. Fort 47 Lysa Gora

In the case of Fort Lysa Gora, results of the analysis of documentation and laser scanning model proved conformity of the Fort layout. However, considerable shift of two mouths of side linking corridors between the barracks and the central bunker has been noticed (Figure 8). In addition, the following have been noticed:

- numerous distortions of embankments and moats, caused by the Polish army troops stationed in the Fort and using it until the 1990s,
- cutting the artillery embankment with a road next to the right shoulder caponiere,
- ground levelling works to the west of the central bunker, and destruction of flanking casemates in the neck recess and left half-bastion,
- backfills in front moats and left shoulder moat, with partly buried caponieres.

The LIDAR model enabled identification of the outline of the demolished gatehouse, which was buried by the ground after 1914. The assembly yard opposite of the barracks, as well as access roads were destroyed and developed by the army in the post-war years with residential and warehousing buildings, and in the beginning of the 21st century a housing estate was built in that area.
Figure 8. Lysa Gora Fort: a) the isolines map obtained from LIDAR date, b) the profile along the A-A' line showing the changes between the archival plans and the current state of the object

5. Conclusions

Austrian archival plans were applied to make 3D models of the forts in the CAD environment. Data from LiDAR (Light Detection and Ranging) and TLS (Terrestrial Laser Scanning) provided a basis for generating a current 3D models of the objects. Based on the comparison of the archival data with the current data, information has been obtained on the differences between original designs and actual implementation of them, and the existence of errors in historic documentation. As a result of the analysis the of models from different periods, it was possible to identify substantial divergences between the condition of the forts in the beginning of the 20th century, and its present-day state. In addition, the effect of the flow time and the impact of natural factors were observed. The influence of erosion as resulting from the natural process of silting drains of forts' ground forms, the blurring of the slopes, landslides of the scarps, flooding of moats and caponieres.

Moreover, the performed analysis made it possible to assess the present-day condition of the examined objects, the scope of demolitions completed to date, and spatial deformations, shaft, moats
distortion and access roads caused by municipal construction projects, or determine the extent of destruction the bastions and caponieres.

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