

The Use of Laser-Scanned Point Clouds for the Virtual Reconstruction of Medieval Hungarian Castles

Ábel Hajas¹ 

¹ Budapest University of Technology and Economics, Faculty of Architecture, Department of History of Architecture and Monument Preservation
abel.hajas@edu.bme.hu

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In heritage conservation research, the use of spatial scanning is becoming increasingly common; however, there are still untapped possibilities in its application. The topic of this article is an overview of terrestrial and aerial scanning, as well as the introduction of methods that have not yet been applied.

At the beginning of the article, I present the principles of true-to-form surveying, which forms the basis of our research. Then I describe the methodology of the surveys and the specific steps required to carry out the analysis. These methods are suitable for producing precise, measurement-ready, geometrically accurate floor plans and for examining masonry fabrics, as well as visualizing them. Furthermore, they make it possible to conduct larger-scale floor-plan analyses that also considers the surrounding geographical features.

This article illustrates the methods by using Hungarian castle ruins examined during my PhD research, although they can be applied to other building types as well. In addition, the article discusses further possibilities of the surveying methods and new directions for the research.

castle, border fortress, 3D scanning, point cloud, geometrical analysis

1. Introduction

The aim of this article is to provide a brief overview of point-cloud scanning and to introduce some methods that we regularly apply in our research. Laser scanning surveys are widely used among civil engineers and surveyors as a modern solution to time consuming site mapping. Although they appear less frequently in the field of heritage conservation, they are becoming increasingly popular. More and more sites are being surveyed using this technology; however, these surveys are unfortunately rarely made public (Halmos, 2025, p. 55). Many datasets are produced, yet due to the additional expertise required for their proper use, they often remain unused, or even when they are utilized, they are not made accessible in any form.

In this article, I present the methods for the use of laser scanned point clouds on Hungarian border fortresses we examined during my PhD research; however, these methods can be applied to any survey that results in a point cloud, regardless of the building's function or condition. The presented methods are suitable for creating accurate, true-to-form floor plans and for carrying out masonry-fabric analyses. Furthermore, they make it possible to conduct larger-scale floor-plan analyses that also consider the surrounding geographical features. Finally, the article discusses additional possibilities for the use of point clouds and new ways to expand our current research.

2. True to form surveying and point clouds

True-to-form surveying is one of the most important methods in modern building research. Its spread was greatly influenced by the work of Manfred Schuller (2002). In essence, geometrically accurate surveying is nothing more than documenting an object by measuring it within a geometric system that is independent of the object (Halmos, 2025, p. 55). However, achieving this requirement does not depend on the use of advanced or modern instruments. In fact, it can be accomplished with the simplest surveying tools, provided the survey is carried out with sufficient precision (see for example the hand-drawn survey

on Fig. 1). The greatest advantage of the true-to-form surveying method is that it seeks to record the object free from any subjective opinion or value judgment. This is what ensures that the survey can be used in later research without potentially missing information.

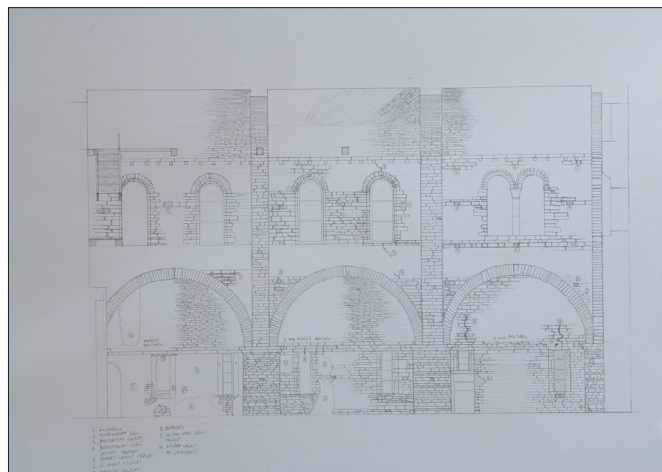


Fig. 1: Hand-drawn survey made on site (Ábel Hajas, 2024)

Laser scanning is now closely associated with true-to-form surveying. It is one of the most widespread methods both in research tasks and in architectural applications. In terms of quality, 3D scanning does not necessarily surpass manual measurement. The measurement accuracy of 3D scanners is between 2 and 6 mm at 10 meters, an accuracy that can also be approached using traditional instruments (Halmos, 2025, p. 58). However, the significant advantage of laser-scanning surveys is that a single scan produces hundreds of thousands of points in a matter of minutes. By combining several of these scans you can create a point cloud of the entire surveyed object.

A point cloud is, in essence, nothing more than a collection of points defined by three coordinates (x, y, z). The millions of points generated during the measurement provide a level of detail that cannot be achieved with any other tool. The large number of points is especially important in surveys where the complex form or large scale of an object makes traditional measurements very difficult. Another advantage of point clouds is that they can be edited, yet they retain their geometric accuracy throughout the editing process.

However, after each individual measurement has been completed, the scans must be imported into specific editing programs and aligned. Furthermore, even after this alignment the surveys still require a considerable amount of work for the relevant information to be readable. At present, post-processing is the greatest obstacle in the use of point clouds. Very few software applications can handle the file formats, and unfortunately there are similarly few specialists who can do so. In addition, the current way professionals and design studios use point clouds also reveals certain shortcomings.¹ Point clouds play a very important role in surveying today; however, their use in currently available 3D programs is far from seamless.

3. Geometrical Analysis of the Construction of Border Fortifications in Hungary in the 16th–17th Centuries – my PhD research

This research focuses on the geometric analysis of Hungarian border fortresses from the 16th and 17th centuries. These two centuries brought significant changes to the design and construction of Hungarian castles. The 16th and 17th century represented a transitional period between the knightly castles of the late Middle Ages and early modern fortifications. It was during this time that the southern Hungarian border-fortress system collapsed, forcing nobles and kings to improve the previously less advanced fortifications in the heartlands of the Hungarian Kingdom. This era was therefore not only a defining period on a European scale, but also a pivotal one in the history of Hungarian castle architecture.

The primary driving force behind the change was gunpowder. Naturally, gunpowder was already known before the 16th century (see Fig. 2). However, the efficiency of early firearms was quite low and did not compel defenders to alter their fortifications (Domokos, 1986, p. 49). By the 1400s and 1500s, however, castle architecture had to evolve in response to increasingly effective artillery.



Fig. 2: The siege of Füleke Castle in 1593 (Lucas Meyer, National Széchényi Library, Régi Nyomtatványok Tára, App. M. 1060)

Previously constructed castles with thin, high walls and inner towers had to be rebuilt – or entirely new ones had to be constructed – to withstand the massive destructive power of cannon fire. (see Fig. 2) The solution against artillery was to build shorter walls, minimizing the surface that could be targeted and destroyed, and to use earthen ramparts capable of absorbing the energy of incoming projectiles (Domokos, 1986, p. 49). These two changes were relatively easy to achieve, yet they were not sufficient on their own. In addition, the fortifications had to provide space for the defenders' own artillery, and the defensive system had to be designed so that no point of the fortress would remain without covering fire. Achieving these changes took considerably longer, as they required the development of an entirely new defensive system.

This replaced the design of medieval castles with a unified system in which every component could properly protect the surrounding sections of the wall.² The first solution to this was the Italian bastion system (Fig. 3), which began to be built in Hungary from the 16th century onward and continued to develop thereafter (Domokos, 1997, p. 184). There were, however, problems with the Hungarian implementations of this system. Due to the terrain the Hungarian forces had to defend, most of these castles were built in hilly or mountainous regions. Areas with significant elevation differences are not ideal for the Italian system. The attackers can exploit certain blind spots the elevation creates, because of this fortification engineers preferred open flat terrains.



Fig. 3: The fortress of Érsekújvár, an example of early Italian fortress architecture (Johann LeDentu, 1639)

In Hungary, this situation resulted in many unique solutions, some of which were very effective, and some which were not so much. Another quirk of Hungarian castles is that there is no clear dividing line between older fortress systems and newer designs. Many fortresses were expanded with long outdated solutions (like rondels and barbicans) (Domokos, 1997, p. 180). Engineers in Hungary strived towards achieving the best possible solutions in the given locations, because of this they had to adapt to the geographical features much more than western European engineers.

The fortresses of the new system were designed by military engineers according to geometric principles, considering the characteristics of the terrain and any existing structures. As a result, these forts can be analysed based on the underlying design principles, allowing the engineers' design methods to be identified. In addition, the effective ranges of contemporary artillery and the methods of siege warfare are well known – and were, of course, known to the military engineers of the time as well. By examining the broader surrounding area, one can also discover, considering period siege principles, how the

designers adapted to the geographical conditions during the planning process (see for example Fig. 4). These two analytical perspectives form the foundation of my research, through which I aim to examine the Hungarian border fortresses from a new point of view.

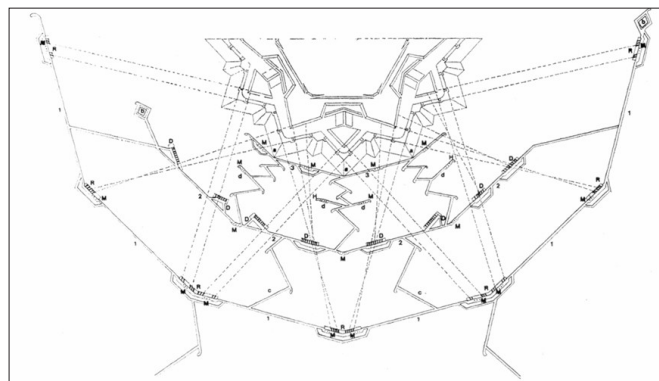


Fig. 4: Siege plan of a fortress according to Vauban's parallel siege method (Domokos, 1986, p. 102)

4. Our method of analysing point clouds

Our examinations are based on the use of point clouds. The surveys themselves are carried out in two ways: Terrestrial Laser Scanning (TLS) and Aerial Laser Scanning (ALS).

During TLS scanning (Fig. 5), the instrument is set up on the ground, and the surrounding area is surveyed from that position. The instrument is then moved to another part of the area that has not yet been surveyed, ensuring that there is overlap between the two measurements. This process is repeated as many times as necessary to fully capture the scanned object. The smaller point clouds from each measurement can be aligned using the overlapping areas. This creates a single point cloud in which the entire object is visible. This surveying method is very precise, capable of capturing even the details of individual stones, and is also excellent for surveying interior spaces and more detailed wall sections.



Fig. 5: Terrestrial Laser Scanning (Photo: Petra Páncél)

In contrast, ALS scanning is conducted from the air (Fig. 6); nowadays, most often using a drone equipped with a LiDAR sensor. This type of survey requires significantly more expertise, as someone must operate the drone, but it is much faster and can cover a larger area. Using this method, an area of approximately 5–10 hectares can be surveyed in about 15–20 minutes. However, aerial scanning is not suitable for surveying interior spaces (since the measurements are taken from above), and it cannot achieve the same level of precision as terrestrial scanning. ALS is far more suitable for surveying large areas.

In our research, both methods are applied: terrestrial scanning is used for surveying interior spaces and wall sections (Fig. 7), while aerial scanning is employed to examine site layouts and the surrounding geographical environment (Fig. 8). Each survey requires separate processing, and the two separate point clouds can be combined if necessary to create a more comprehensive survey.



Fig. 6: Aerial Laser Scanning with LiDAR using a drone (Photo: Ábel Hajas)

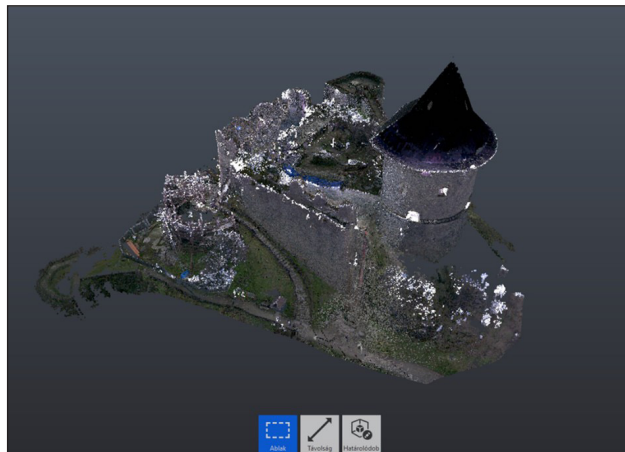


Fig. 7: TLS scan of Somoskő castle

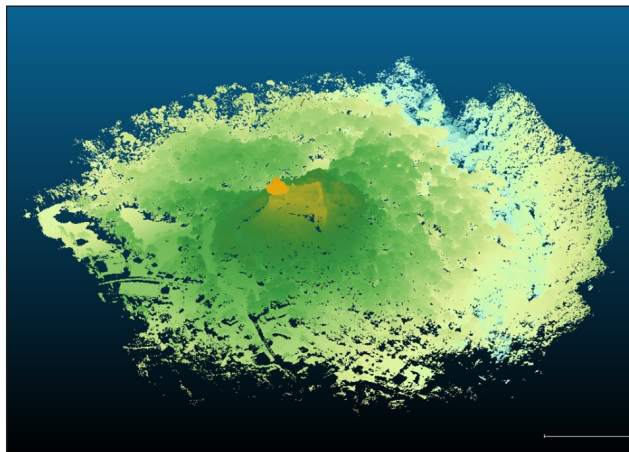


Fig. 8: ALS scan of Somoskő castle

4.1 Creating a site plan

The first step in the research is to produce an accurate and reliable site plan. This is particularly relevant in our case, as many of the currently available castle plans are only indicative or are based on inaccurate or outdated surveys. The initial step, therefore, involves creating such a plan, either based solely on the terrestrial survey or using a combined approach.

The terrestrial scanning is performed with a Leica BLK360 scanner provided to us by the department of History of Architecture and Monument Preservation from Budapest University of Technology and Economics. The individual scans are aligned using the Leica Cyclone Register 360 software. Subsequently, unnecessary elements, such as portions of vegetation and foliage or unnecessary structures, are removed using AutoCAD Recap.

From the cleaned point cloud, 1 cm-thick slices are then extracted at regular intervals in AutoCAD. Each 1 cm slice traces the contour at the corresponding height. By repeating this process at consistent intervals, a topographic representation of the site is created once the slices are stacked (Figs. 9 and 10). Since this drawing is based on the point cloud, it provides an extremely accurate representation of the actual castle ruins.

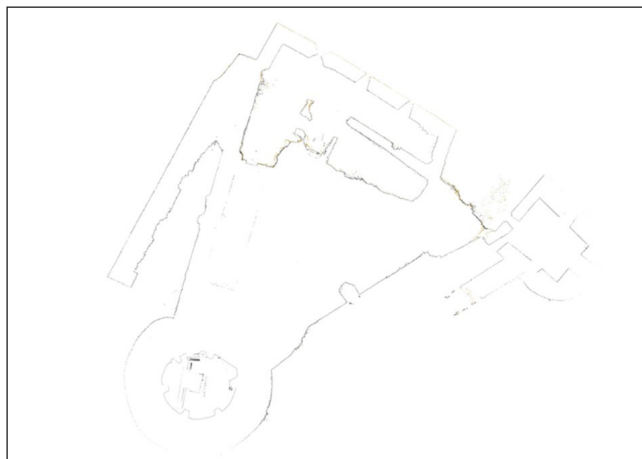


Fig. 9: A single 1 cm thick slice cut from the merged point cloud of Somoskő castle

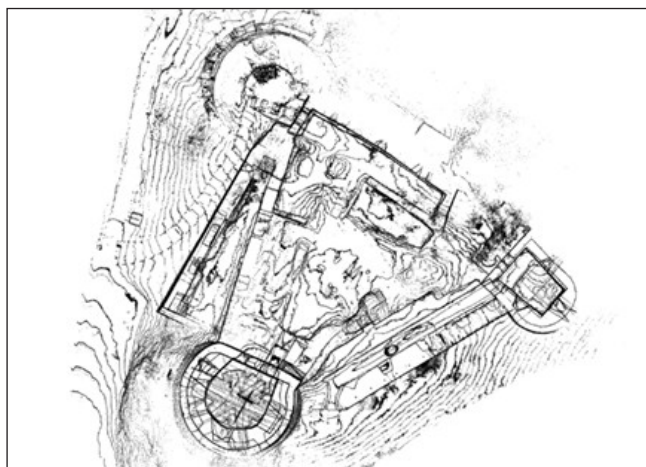


Fig. 10: All the slices combined into a topographic plan of Somoskő castle

However, in this form, it cannot yet be considered a proper site plan. To produce a final plan, the topographic drawing must be further refined. The final plan is developed by selecting, for each section, the slice or slices that best represent that particular area. While some information is inevitably lost in this process, the result is a highly accurate site plan that can be used for measurements and to draw research-based conclusions (Fig. 11). In case any more details or information is necessary, one can always go back to the original topographical drawing, or to the point cloud itself.

The site plan created with this method is suitable for geometric analyses as well as for examining the artillery-related aspects of the surveyed location. It allows for determining the types of fortifications constructed by the defenders, their lines of sight over the surrounding area, and the most likely positions from which attackers could have deployed their artillery.

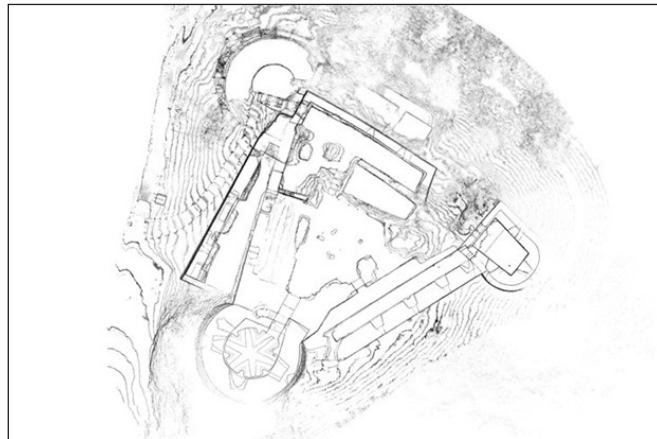


Fig. 11: Site plan of Somoskő castle after cleaning the topographical plan

4.2 Analysis of wall structures

However, the plan alone is not suitable for a detailed analysis of individual wall surfaces. For such studies, an orthogonal view of each section must be examined. During this examination it is important that the most important features are clearly represented. To achieve this, we have developed another analytical method.

The first step is to create a 3D model using the accurate site plan and the point cloud in an architectural design software. We use Archicad but any such software will suffice. The model does not need to be perfect; however, the goal is to make it fit the actual ruins as closely as possible. Some simplifications are applied during the modelling process: certain walls are modelled as straight lines if their deviation is relatively minor, or they are modelled by using several smaller straight sections. Curves are approximated, usually to fit the measured curve as much as possible. The result is a model created in the design software based on the present-day ruins, but due to the software's element set, all wall surfaces are perfectly flat. This regularity is particularly important for subsequent comparisons.

After the model has been created, it is imported into the software CloudCompare, which can perform various operations and comparisons with point clouds. The Archicad model is not initially in point cloud format upon import (Fig. 12), but this can be easily resolved through a conversion process (Fig. 13). During the conversion, the number of points can be specified, thereby increasing the accuracy.

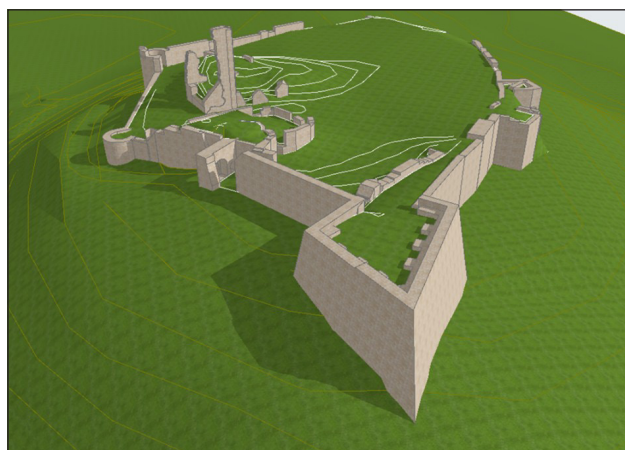


Fig. 12: Archicad model of Nógrád castle created based on site plan and point cloud

The two separate point clouds are then aligned as precisely as possible. CloudCompare provides algorithms for this purpose, and the alignment can subsequently be refined manually. Once the alignment is completed, the two separate point clouds can be directly compared.

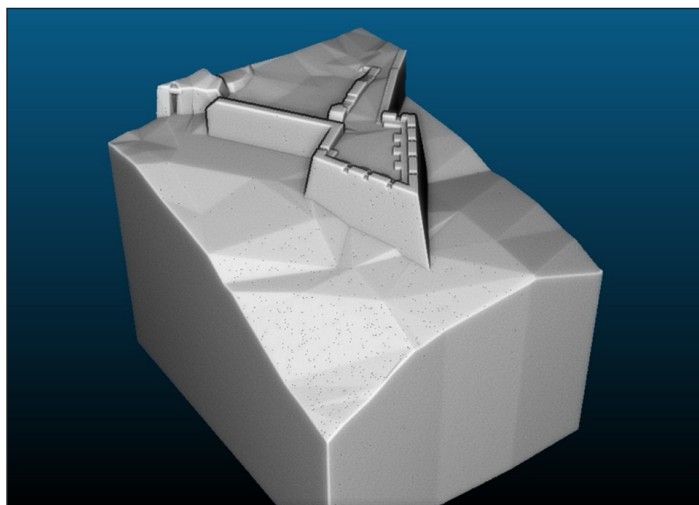


Fig. 13: A section of the Archicad model of Nógrád castle converted to point cloud

The comparison is performed using the "Cloud-to-Cloud Distance" tool, which measures the deviations of one point cloud relative to another in the x, y, and z directions. In this case, the reference is the "regular" Archicad model, and the original point cloud is compared to it. The operation visualizes the deviations on the original point cloud using a heat map.

When examining wall surfaces, the z-direction can be disabled, as deviations in the horizontal plane are more informative for our purposes. This approach produces a visual representation that highlights the irregularities of the wall surfaces relative to the interior regular model, resulting in a much more interpretable image (Fig. 14).

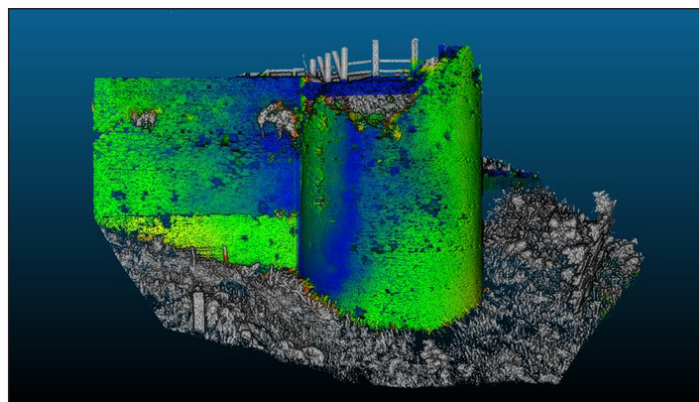


Fig. 14: Heatmap comparison of a portion of Nógrád castle in the x-y plane, levelling courses and missing elements are all visible

Using the comparisons produced during our research, it is possible to determine the properties of the wall fabric, such as levelling courses used during construction.³ Protrusions, repairs, faults in the walls, as well as traces of later modifications and reconstructions, can also be identified. Additionally, the z-direction can be useful in cases where dense vegetation obscured sections of the walls during the survey. If an accurate site plan is available – either obtained through the survey or from previous sources – it is possible to determine the extent of the walls in the original point cloud. This is done by modelling based on the site plan and by creating walls that extend beyond what remains today. Using the z-axis comparison, we can draw the outlines of the current structures even if vegetation obscured them or if during the survey that area was not recorded in sufficiently detail.

These two survey methods thus provide the means to create accurate site plans of the surveyed locations, which can be used for measurements and further research. Such site plans also enable the study of the construction of defensive systems and, when combined with LiDAR measurements, allow for the consideration of the surrounding terrain in the analysis. Wall surface examinations, on a smaller scale, make it possible to investigate construction layers and individual wall sections, thereby offering insights into the building history.

5. Further methods and possible collaborations

Our research initially focused on Nógrád Castle, where the survey and analysis methodology was first developed. However, no publication has yet been produced specifically about this site.

Currently, a publication is being prepared on Somoskő Castle, which serves as a case study and represents the first application of the methods described above. The article primarily examines the castle's design methods and the surrounding geographical conditions, aiming to understand the intentions of its planners. In addition, the analysis of wall surfaces is intended to provide insights into the construction history of the castle.

In later stages of the research, the goal is to extend the methodology to larger fortresses and to study sites that are closer in design to the modern fortifications of the 16th–17th centuries. Possible locations for such studies include Nyitra and Léva Castles.

In addition, we are currently exploring the possibility of collaboration with departments that have greater expertise in geoinformatics. By combining their surveying methods with our approach, we aim to develop additional analytical techniques, such as examining lines of sight from specific positions or implementing faster scanning procedures.

Notes

¹ In architectural CAD programs during post-processing, they create 2D sections from the 3D point cloud and then this 2D section is modelled into a 3D model in the CAD program. These multiple transformations not only lead to inaccuracies but also require a significant amount of work. (Halmos, 2025, p. 66)

² There were many systems that were tried at this period, Italian Bastion fortresses were one of the first and they were the most widespread. Later systems iterated on this system.

³ These were used to ensure the courses in the wall fabric don't deviate too much from the horizontal plane.

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