MŰEGYETEM 1782

Budapest University of Technology and Economics
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Comparison Analysis of Point Cloud Techniques Used for Developing a BIM System

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1. Introduction:

Different surveying methods have been utilized throughout centuries for designing and constructing incredible structures across the globe. With the advancement of the construction and adjacent industries, surveying methods have also transformed, becoming faster, more efficient, and accurate.

Traditional surveying techniques that use tools such as theodolite and total station have been around for a long time. Their accuracy has been a subject of numerous research works [e.g. Dzierzega és Scherrer, 2003; Singh et al, 2002; Walser, 2004]. Even with several possible errors that occur during such measurements, these methods are still regarded as highly accurate and a fine standard for various surveying works.
21st-century engineering deals with more complex designs than ever before. The surveying technology has quickly adapted to the new era, offering smart solutions for new challenges.

A point cloud survey is an incredible breakthrough for the field [Berger et al., 2016]. It employes various types of laser scanners: static, handheld, and attached to UAVs. They send out millions of laser beams in all directions. The beams hit the surface and are reflected, returning to the scanner. Millions of reflected points create an incredibly detailed picture of a building.

Various point cloud surveys were performed on the “Jó Szerencsét!” cultural center in Várpalota by Máté Lehoczky. A number of modern point cloud technologies were utilized during the process to get the best outcome.

The exterior of the building was surveyed with a UAV and a static laser scanner. Measurements on the interior were made by a handheld scanner. The work has resulted in a comprehensive point cloud dataset, consisting of hundreds of millions of points. The survey will be used in the preparation of design concepts and the creation of a Building Information Modelling (BIM) system for a major renovation project of the “Jó Szerencsét!” cultural center.

This research aims to use the point cloud survey of the cultural center in a comparative analysis of the laser scanner technologies used during the process. The point cloud data were compared to measurements of particular points taken by a total station and a handheld mobile scanner.

Traditional surveying methods are assumed to be accurate within the framework of this study. The research aims to understand and evaluate the accuracy, reliability, and efficiency of applied point cloud technologies.

2. The technologies used for point cloud measurements

This section reviews three types of instruments used in point cloud surveys of the building. The exterior of the building was surveyed using two different technologies. The first one is the static laser scanner from Leica Geosystems - Leica ScanStation P40. The Phantom 4 PRO UAV was used for the external surveying of parts of the building that are not visible from the ground.

2.1. Leica ScanStation P40

Leica ScanStation P40 is a high-definition 3D laser scanner, designed and manufactured by Leica Geosystems. This instrument is based on the Time-of-Flight (TOF) and WaveForm Digitizer (WFD) distance calculation methods. The TOF technology uses the time it requires for an emitted light pulse to hit the surface and return to the scanner. Leica no longer uses only TOF technology in their instruments, since the method lacks high accuracy. Instead, the TOF and phase-shift methods are combined to create a much more precise way of surveying. This technology is called WaveForm Digitizer (WFD). It is important to note, that the WFD is still primarily a TOF type, featuring some benefits of phase-shift technology. As a result, Leica ScanStation P40 has extensive abilities.

The Light Detection and Ranging (LIDAR) software Leica Cyclone was used for 3D point cloud processing.

Table 1. Specifications of Leica ScanStation P40

Range accuracy	1.2mm + 10ppm over full range
Angular accuracy	8" horizontal; 8" vertical
3D position accuracy	3mm at 50m; 6mm at 100m
Wavelength	Invisible: 1550nm / Visible: 658nm
Scan rate	Capable of 1,000,000 points per second
Range	Up to 270 meters
Field of view	Horizontal: 360° / Vertical: 290°

Figure 1. Leica ScanStation P40, Leica GeoSystems

2.2. UAV DJI Phantom 4 Pro

Figure 2. DJI Phantom 4 Pro UAV

The DJI Phantom 4 Pro UAV was used to survey the parts of the building that are not visible from the ground. Yet, the entire facade of the building was covered using the

UAV. The drone is equipped with a 1 inch, 20-megapixel sensor, capable of recording 4K footage. It has forward, backward, and downward vision systems, as well as a flight range of up to 7km. The UAV can capture the most remote parts of the building in detail.

The footage gathered from the UAV needs photogrammetric processing in order to be useful for surveying purposes. The photogrammetry software Agisoft Metashape was used to produce the spatial data from the DJI Phantom 4 Pro footage.

Figure 3. inch, the 20-megapixel camera of DJI Phantom 4 Pro

2.3. Leica BLK2GO Handheld Imaging Laser Scanner

The entire interior of the building was surveyed using the Leica BLK2GO handheld scanner. The scanner is wireless and fast. It has the ability to scan under and over objects throughout space. The instrument automatically creates 3D point clouds during motion. Its SLAM spatial awareness technology enables the instrument to locate itself precisely inside of the building. As a result, Leica's scanner recognizes spaces it has already covered. Due to the scanner's fast and convenient nature, the survey of the interior was done in an extremely short timeframe - approximately 2 hours. On the contrary, interior surveys performed with traditional methods can take much longer, while being more complex to execute.

Figure 4. Leica BLK2GO Handheld Imaging Scanner

3. Instruments used for measurements with traditional surveying methods

Three surveying technologies used for performing measurements with traditional methods are covered throughout this section.

3.1. Trimble M3 3" Total Station

Reference points of the building's facade were surveyed with Trimble M3 3" total station. It is a mechanical total station, featuring both traditional prism reflector (PR) and direct reflex (DR) technologies. The latter ensures that certain hard-to-reach points on the facade, such as window and door corners, or parts of the roof, can be accessed. The instrument is equipped with Nikon optics, as well as software provided by Trimble.

Table 2. Specifications of M3 3" Total Station

Accuracy in prism mode	±(3 mm + 2 ppm)
Direct Reflex mode	±(5 mm + 2 ppm)
Range in prism mode	Up to 5000 meters
Range in Direct Reflex mode	Up to 210 meters

Figure 5. Trimble M3 3" Total Station

3.2. Leica GS18 I GNSS RTK Rover

Leica GS18 I GNSS RTK survey-grade rover was used for locating station points. The instrument has a 20Hz position update rate, making it particularly accurate and responsive.

Figure 6. Leica GS18 I GNSS RTK Rover

3.2. Leica Disto D5 laser measure

Measurements of the building's interior were performed using Leica's Disto D5 laser measure. The instrument is equipped with a built-in tilt sensor and a digital video point finder. It is able to measure distances up to 100 meters without a target plate, or even up to 200 meters with an appropriate target plate. The laser pinpoint accuracy is ± 1.0 mm.

Figure 7. Leica Disto D5 laser measure

4. The general overview of the point Cloud dataset

4.1. Cloudcompare - the software used for analyzing the point cloud data

Cloudcompare is an open-source, free-to-download, independent software for processing 3D point cloud data. It was used for merging and cleaning point clouds from both the UAV and the static laser scanner.

The software has a number of features utilized for not only processing but also for analyzing the point cloud. Various statistics features help in deeply understanding and studying the data. Besides some general computations, Cloudcompare is also able to perform the spatial chi-squared test and a variety of statistical tests and computations.

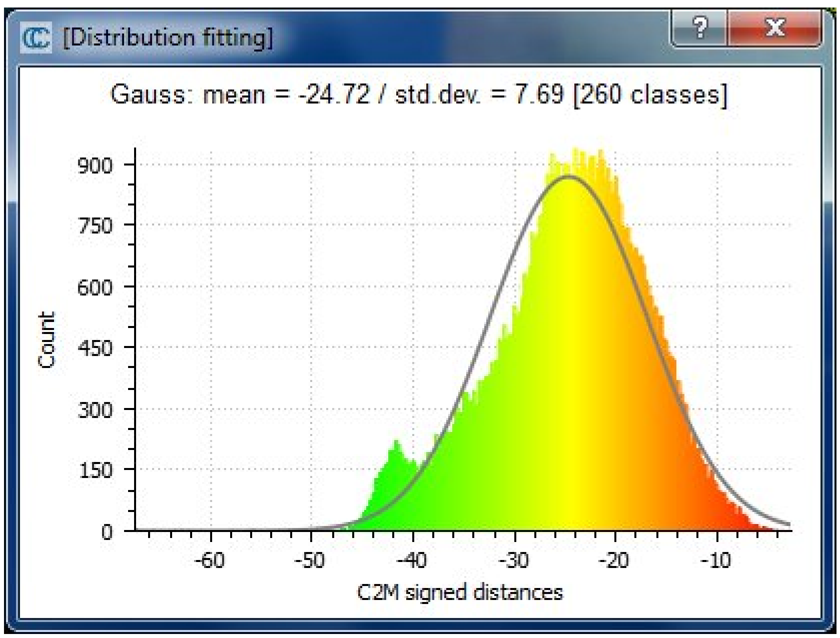

Figure 8. chi-squared distance as an output in Cloudcomp

For further accuracy of point-picking in the point cloud, the software also features the segmentation function. The building can be easily sliced into preferred sections, providing better access to desired points.

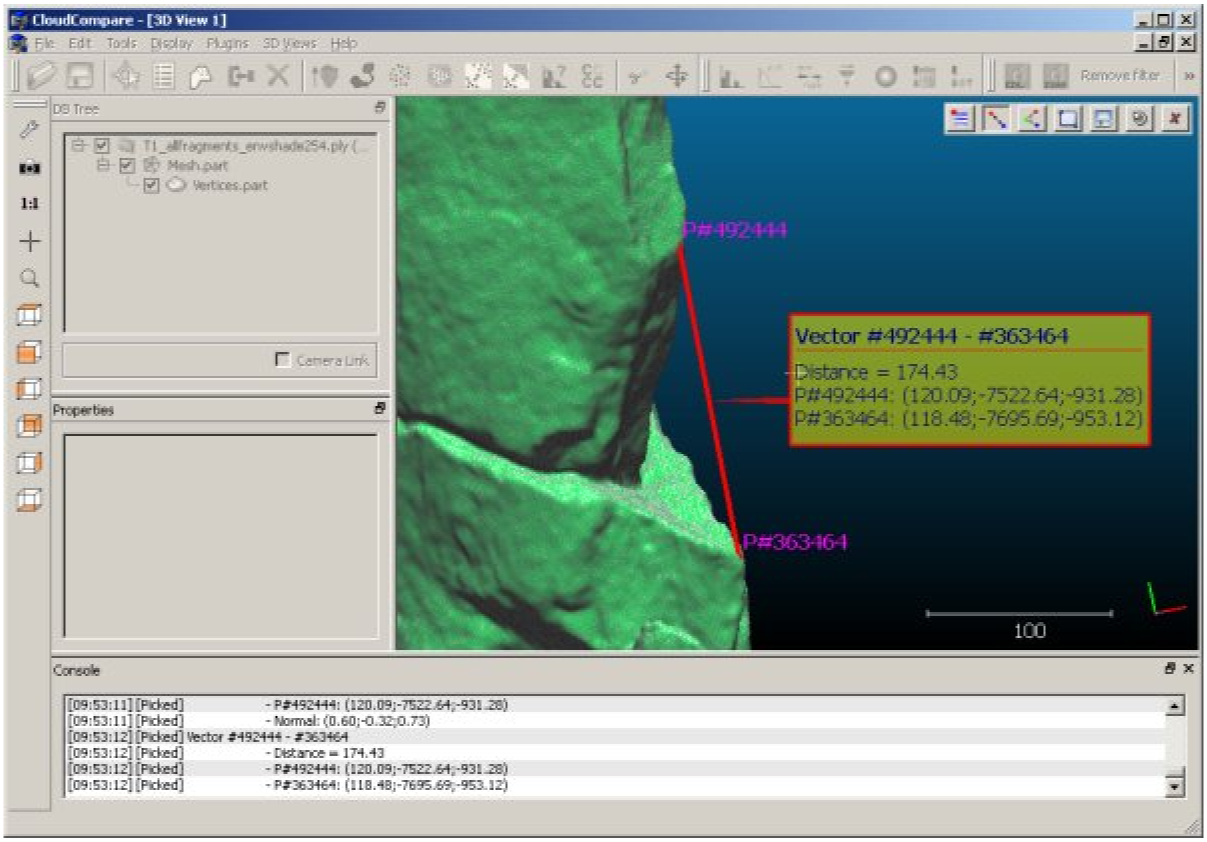

Figure 9. Cloudcompare's distance measurement feature

Cloudcompare's distance measurement function for the point cloud is used within this research to determine distances inside of the building.

4.2. Key statistical findings in the data

All three point cloud datasets together represent an incredibly detailed survey of the building. The total number of points across the 3 datasets is 292,347,527. The DJI Phantom 4 Pro point cloud is the densest dataset, with the most points - 200,861,734, It is followed by the Leica P40 ScanStation static scanner point cloud with 72,572,600 points. The interior survey executed with Leica BLK2GO features the smallest number of points at 18,913,193.

The intensity distributed across point clouds is an important characteristic in understanding and utilizing these datasets. It represents the strength of the reflected laser pulse returning to the scanner. This component of points offers even a better perspective over the coverage, accuracy, and range of different surveying methods. The range of intensity is defined on the scale from 0 to 1, with 0 standing for no and 1 for the highest intensity.

The exterior survey performed with Leica P40 ScanStation showed a varied picture regarding intensity. The vast majority of all points are located on the left side of the histogram amid their low intensity. However, there is a high number of very high-intensity points that can be found at the opposite end. Yet, the histogram shows that almost 55% of all points had lower intensity than 0.2.

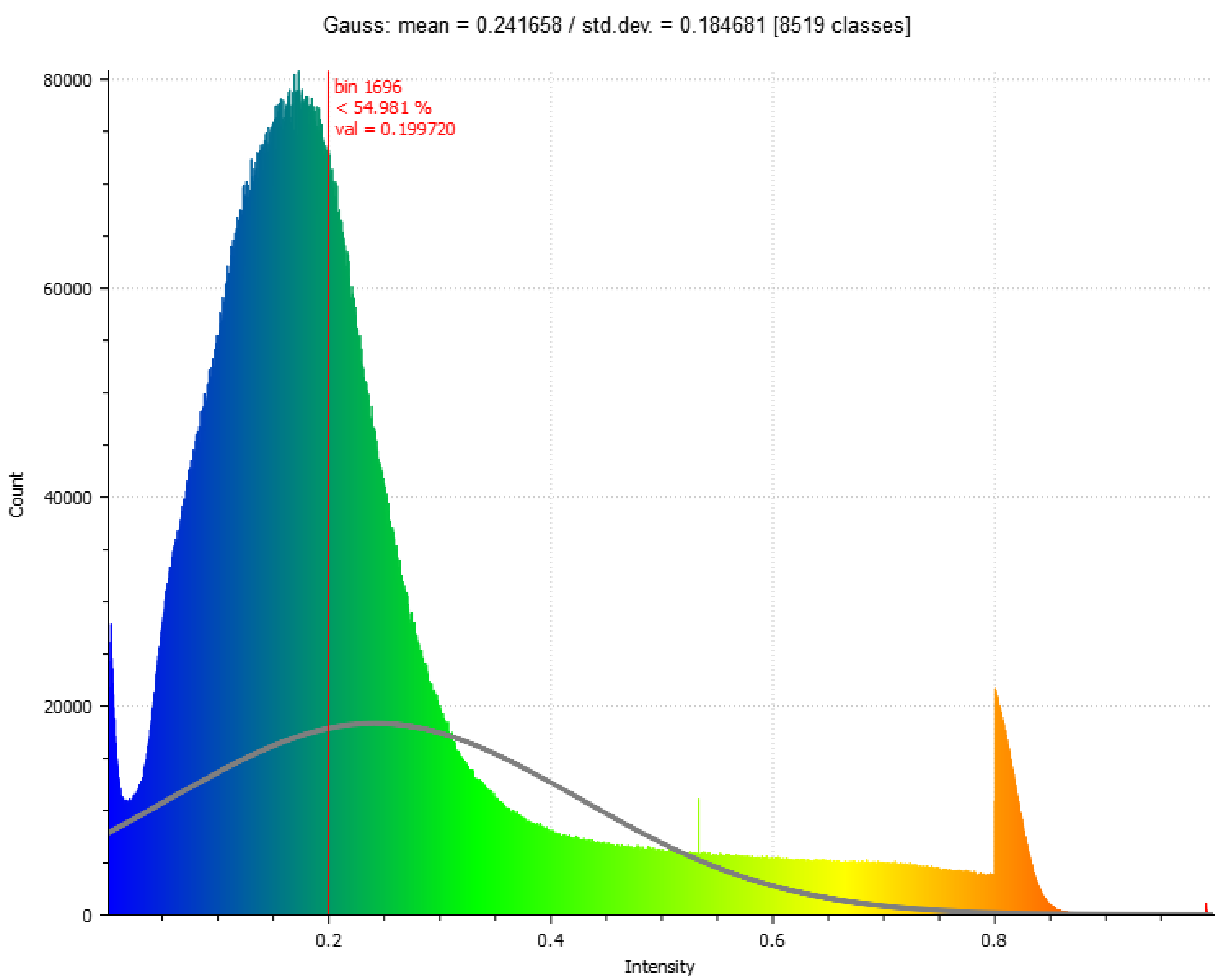

Figure 10. The histogram illustrates the intensity of points in the Leica P40 ScanStation point cloud, along with the mean value and standard deviation.

The mean value of intensity across all points is 0.241658, while the standard deviation stands at 0.184681. Therefore, it is fair to say that the points in the dataset are overwhelmingly low intensity.

The reason for this is that the static laser scanner also surveyed the area around the building, including the greenery, adjacent buildings, and infrastructure. It also features parts of the roof that are rather low intensity, which can be because of the range, the bad sight, or other reasons. The view over the building in the point cloud shows the distribution of high and low-intensity points well. While the vast majority of low-intensity(Blue) points are located in the surroundings of the building or on the roof, the facade also features areas with medium-intensity(green) points.

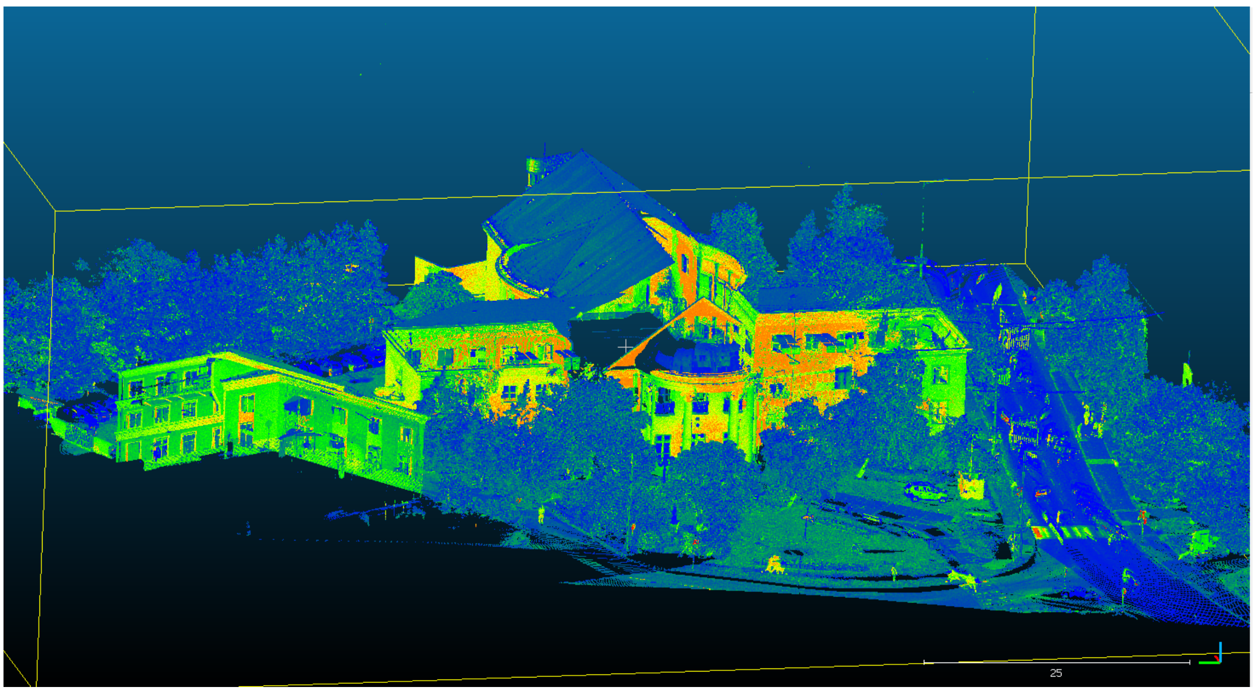

Figure 11. Intensity distribution across the building(blue being the lowest and red the highest intensity), as seen in the Leica P40 ScanStation point cloud

The interior survey also features a high number of low-intensity points. Yet, the shift towards the high-intensity side of the histogram is much more dynamic and gradual in this case. There is a great number of points between the values of 0.2 and 0.5.

The reason for the low intensity in interior surveying can be the environment it is performed in. The low lighting and characteristics of various objects might result in low reflectivity, hence the distribution of intensity across the interior of the building.

The mean value of intensity, in this case, is 0.230330, while the standard deviation is equal to 0.177365. Although the mean value is lower than in the case of Leica P40 ScanStation, the standard deviation is also smaller. This means that intensity values are more equally distributed across points. The latter can be clearly observed in the histogram below.

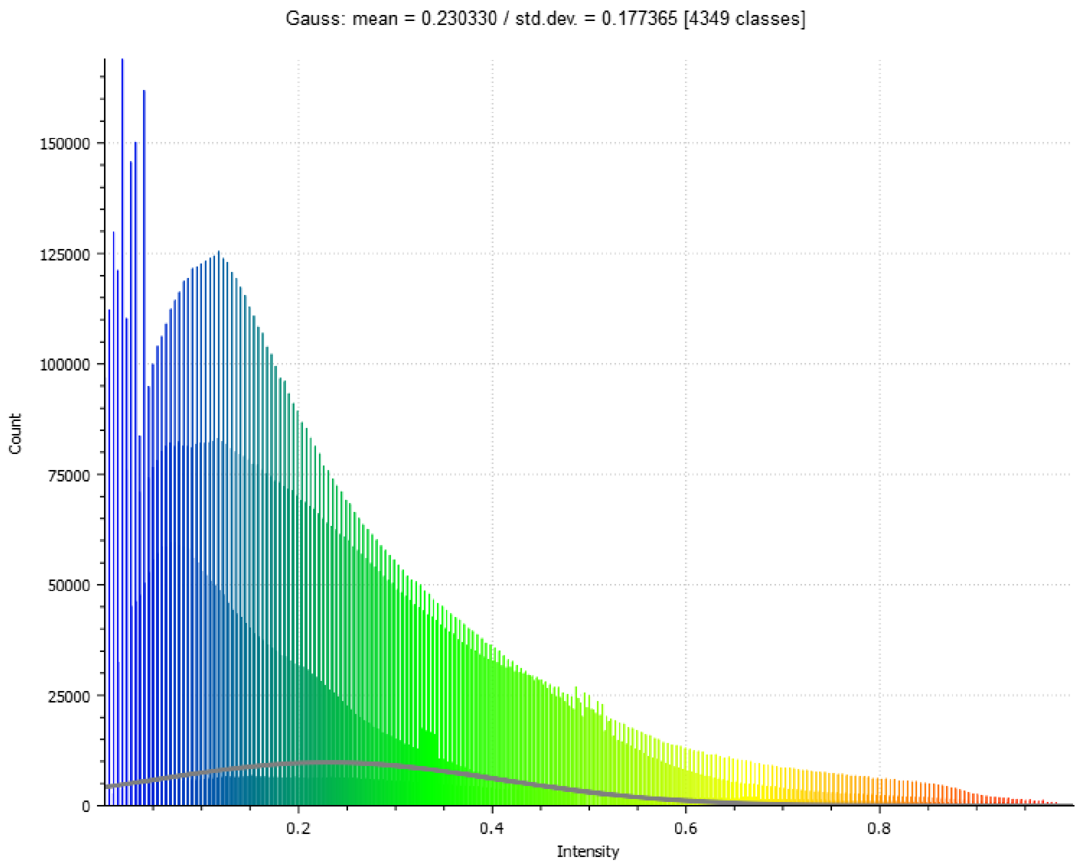

Figure 12. The histogram illustrates the intensity of points in the Leica BLK2GO point cloud, along with the mean value and standard deviation.

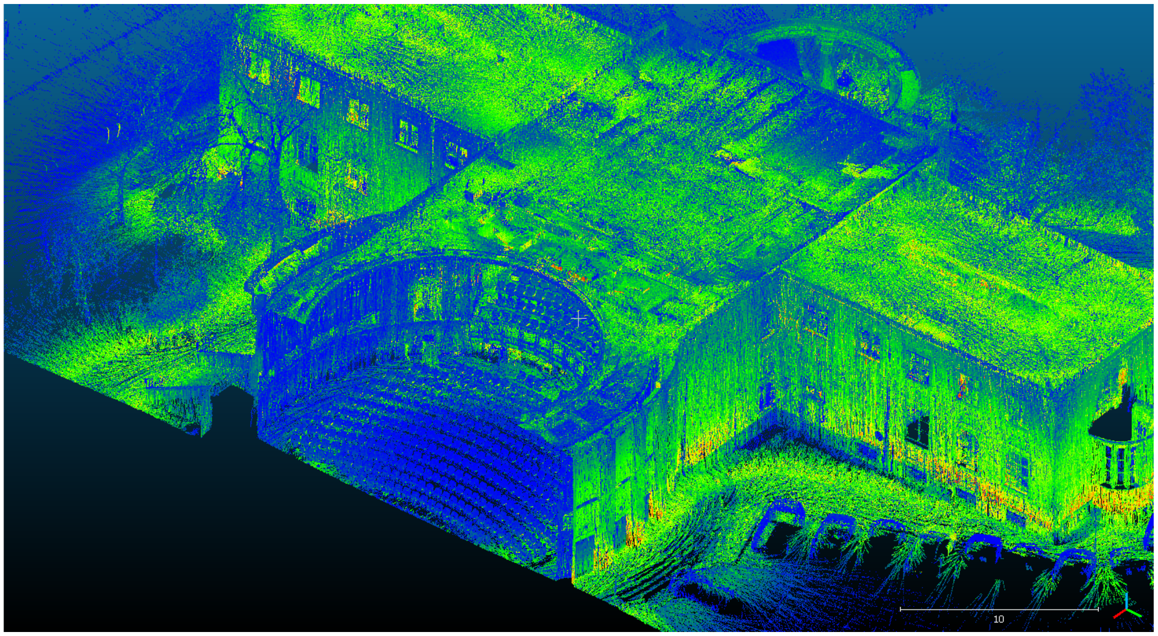

Figure 13. The section through the hall inside of the building, where blue color represents low-intensity points

4.3 The graphical representation of the building in the point cloud

The datasets are represented in Cloudcompare richly. The UAV data is presented in the RGB color model but can be modified to have no color. The Leica P40 ScanStation point cloud is represented in both RGB and Scalar Field.

The point colors in the Leica P40 point cloud are more precisely allocated across the exterior of the building. On the contrary, some parts of the facade are not very well represented by the UAV data. Points are more scattered and corners, lines, and borders between different parts of the building are more difficult to distinguish from one another.

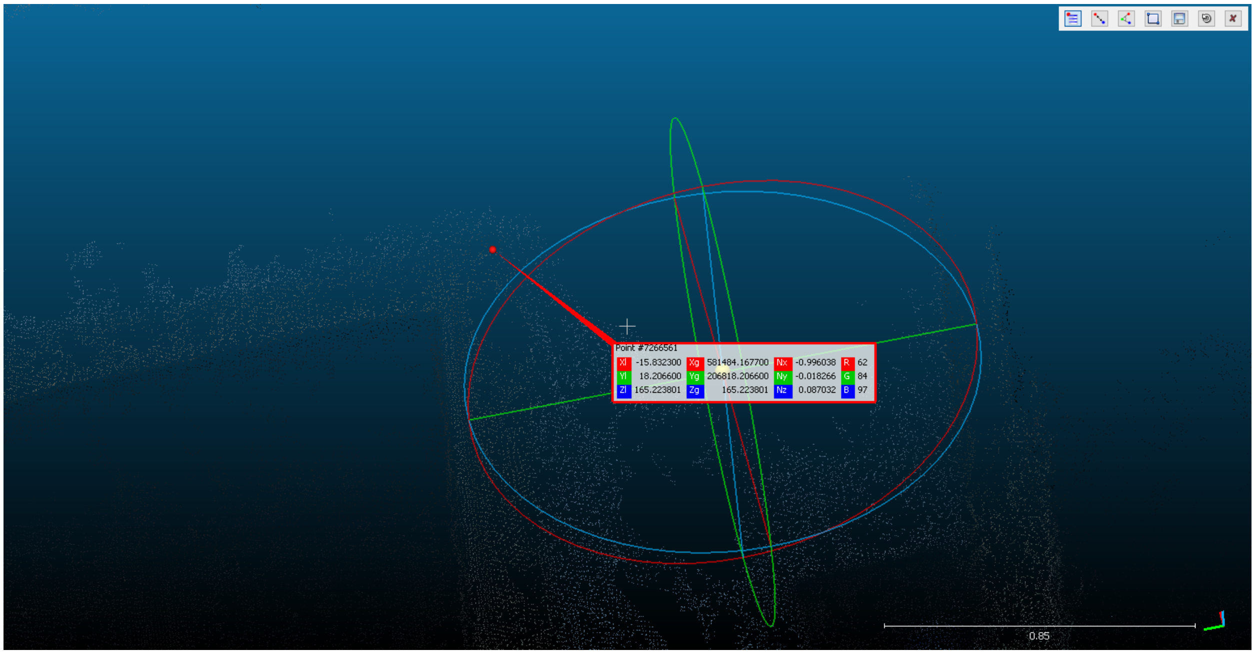

Figure 14. outer borders of the door frame are not precisely visible in the UAV point cloud as color

5. Measurements

5.1. The process of measurement with traditional surveying methods

Several easy-to-spot points were chosen on the western facade of the building for measurements with traditional methods. This part of the exterior features a number of elements, including a dome, ornamental pieces, and columns. The survey was performed on a sunny, clear day, in standard weather conditions. These points had to be then accurately positioned in the point cloud. Therefore, the list of the points consists of door and window corners, central points of the facade ornaments, parts of the roof, and more.

Besides their visibility, other criteria were also taken into account when choosing the points for comparison. Since different circumstances affect the measurements, points were chosen to have vastly varying characteristics. Some of them are surrounded by solid bodies from all sides (e.g. centers of ornamental pieces, window corners), while others are corners on the outskirts of the building or balconies (e.g. roof corner points, balcony corners, fences). The diversity of points' features help in understanding the impact of different circumstances on measurements.

The Trimble M3 3" total station was used for performing surveying on the exterior of the building. In the beginning, the station coordinates were determined using the Leica

GS18 I GNSS RTK Rover (stations labeled as 1S and 23S). Subsequently, 20 points were measured from station 1S and 10 from station 23S. The detail points were labeled consecutively from 1 to 30.

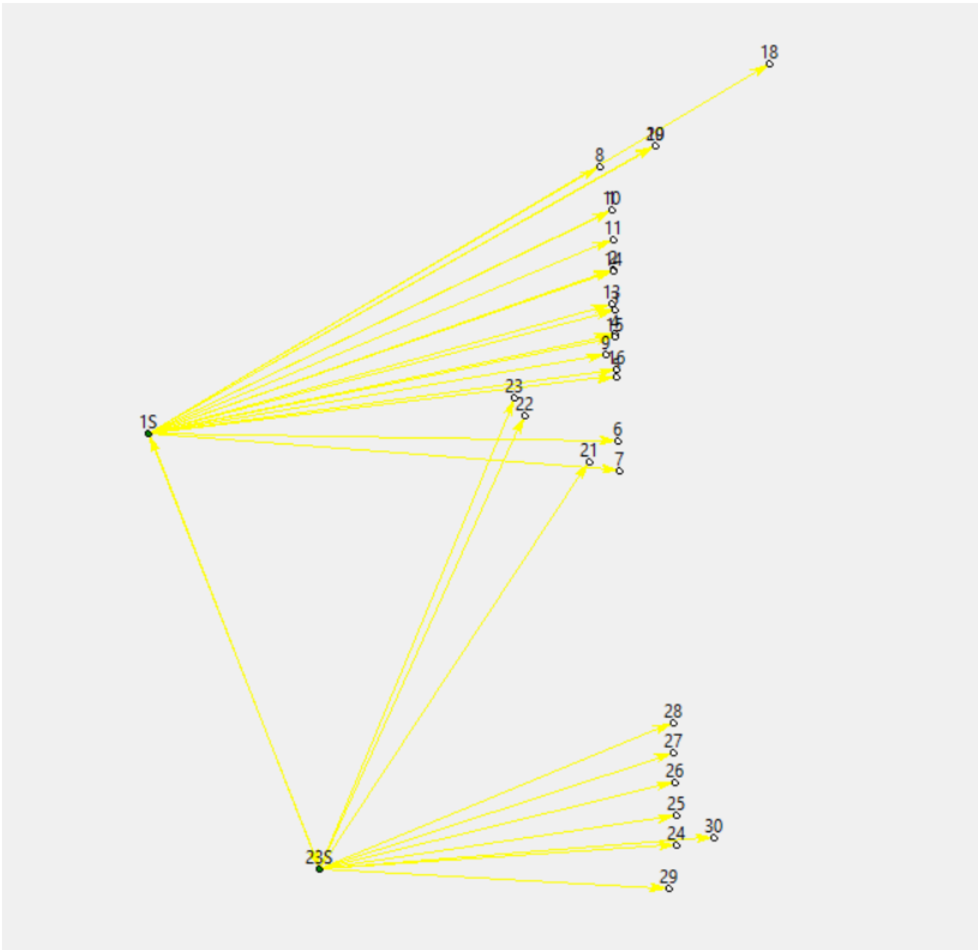

Figure 15. The automatically generated sketch of measurements on the facade, software: GeoEasy

Since most of the points are not physically accessible to humans, the prism would not be a feasible option for measurements. Therefore, the Direct Reflect (DR) model was used for surveying all points on the facade of the building. Even without the prism, the Trimble M 3 3” total station ensures a fair quality of accuracy at ±(5 mm + 2 ppm).

Table 3. The list of the reference point coordinates on the exterior of the building (Trimble M3 3")

Point ID	X	Y	Z
1	581484.026	206823.221	165.912
2	581484.099	206820.244	165.212
3	581484.159	206818.162	165.211

M Ű E G Y E T E M 1 7 8 2

4	581484.162	206816.976	165.173
5	581484.212	206814.84	165.177
6	581484.356	206811.595	165.211
7	581484.412	206810.091	165.927
8	581483.388	206825.391	171.687
9	581483.704	206815.92	178.598
10	581484.01	206823.231	169.767
11	581484.06	206821.755	169.762
12	581484.002	206818.469	168.245
13	581484.118	206820.17	168.298
14	581484.196	206816.82	167.057
15			
16	581484.254	206815.158	169.657
17			
18	581491.942	206830.605	176.193
19	581486.182	206826.502	169.912
20	581486.2	206826.443	166.537
21	581482.86	206810.562	170.362
22	581479.63	206812.869	170.381
23	581479.142	206813.768	170.372
24	581487.292	206791.202	169.782
25	581487.238	206792.697	169.784
26	581487.182	206794.383	169.788
27	581487.134	206795.872	169.78
28	581487.086	206797.382	169.935
29	581486.853	206789.01	171.668
30	581489.171	206791.588	173.413

Both UAV DJI Phantom 4 Pro and Leica P40 ScanStation managed to capture the majority of reference points chosen for the research on the facade. However, certain points were inaccessible to both the UAV and the static laser scanner. These points will be further discussed in the next chapters.

The interior of the building was surveyed using Leica Disto D5 laser measure. The mobile scanner measured Distances in various rooms and spaces inside of the building. Measurements of both small and large rooms were taken to understand the accuracy of the point cloud in varying circumstances. Ceiling heights (floor to ceiling) were also measured in certain rooms.

The large disused hall that served as a theater was measured in perpendicular directions (length and width). This space has a curved shape, putting point cloud's accuracy to test. Moreover, the length of the building (from the entrance doors towards the stage) was measured from the balcony gallery on the first floor. This way, the Leica BLK2GO scanner's ability to accurately measure large spaces can be further inspected.

Understanding the scanner's capacity of precision with smaller-sized objects is crucial, too. For this purpose, the measurements of the column located on the first floor were taken. The diameter of the column was determined using the length measurement performed with a standard measuring tape.

Table 4. Some test measurements in the interior of the building

Distance ID	Measurement in meters (Leica Disto D5)
1	2.168
2	4.963
3	13.343
4	3.125
5	20.503
6	7.323
7	17.035
8	8.001
9	21.76
10	5.627

The aforementioned column had a circumference of 166.2 centimeters, as measured with a traditional measuring tape. As such, the Diameter and the Radius would be the following:

$$C = 2\pi \times R$$

$$R = C/2\pi$$

$$R = 26.45 \text{ cm}$$

$$D = 52.90 \text{ cm}$$

5.2. Building's exterior survey with the DJI Phantom 4 Pro UAV

The survey performed using the DJI Phantom 4 Pro was processed with the photogrammetry software Agisoft Metashape. The point cloud covers the majority of the building's exterior. It is particularly useful for areas of the roof that can not be sighted from the ground using a static laser scanner.

The precision and density of the point cloud are particularly good in the upper parts of the building, including all parts of the roof. However, parts of the building's facade with columns, trees, and other solid objects in front of them are poorly represented in the point cloud. As a result, the dataset (Table 5) given below does not include 6 points from the facade.

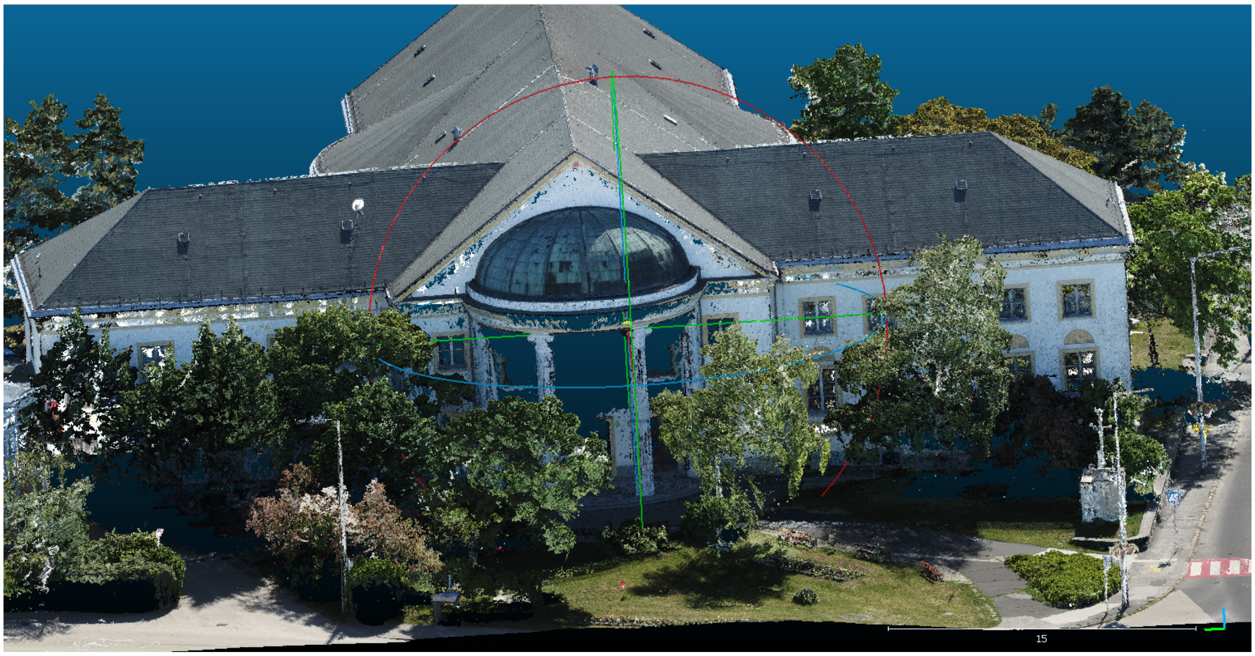

Figure 16. The western facade of the building as seen in the DJI Phantom 4 Pro point cloud

Besides the building itself, the UAV point cloud also features the surrounding area, including the greenery, the terrain, and road infrastructure.

Table 5. Dataset from DJI Phantom 4 Pro point cloud

Point ID	X	Y	Z
1	581484.0957	206823.1953	165.892502
2	581484.1498	206820.2353	165.196594
3	581484.1677	206818.2066	165.223801
4	NaN	NaN	NaN
5	581484.2684	206814.8421	165.187195
6	581483.1233	206811.3346	165.6521
7	581484.3911	206810.0575	165.870895
8	581483.4568	206825.3581	171.654007
9	581483.7749	206815.9248	178.592896
10	581484.0976	206823.3603	169.890198

11	581484.1348	206821.5654	169.898407
12	NaN	NaN	NaN
13	NaN	NaN	NaN
14	NaN	NaN	NaN
15	NaN	NaN	NaN
16	NaN	NaN	NaN
17	581491.6315	206826.8436	175.8983
18	581492.1595	206826.619	176.259003
19	581486.2869	206826.4832	169.852905
20	581486.3055	206826.3958	166.528397
21	581482.8258	206810.5834	170.345306
22	581479.642	206812.8949	170.369995
23	581479.1557	206813.8039	170.362
24	581487.132	206791.0522	169.895905
25	581487.0784	206792.8128	169.892105
26	581487.0442	206794.223	169.875107
27	581487.0031	206795.9903	169.882095
28	581486.9623	206797.3753	169.905594
29	581486.634	206789.0128	171.632599
30	581492.9249	206795.5719	176.239304

All aforementioned 6 points that could not be determined in the UAV point cloud are located in the area covered by a dome and surrounded by columns. Only one point out of six is located on the ground floor - the upper left corner of the middle entrance door. The remaining 5 points are located on the first floor. One of them is in the upper right corner of a window, while the remaining 4 are located in different parts of 2 balconies.

During the processing of the points on balconies surveyed by the Trimble M3 3" total station, an error linked with the Direct Reflex (DR) mode of measurement was detected. The latter is further discussed under the chapter "Errors".

Figure 17. The focus area of the western facade of the building as seen in the DJI Phantom 4 Pro point cloud

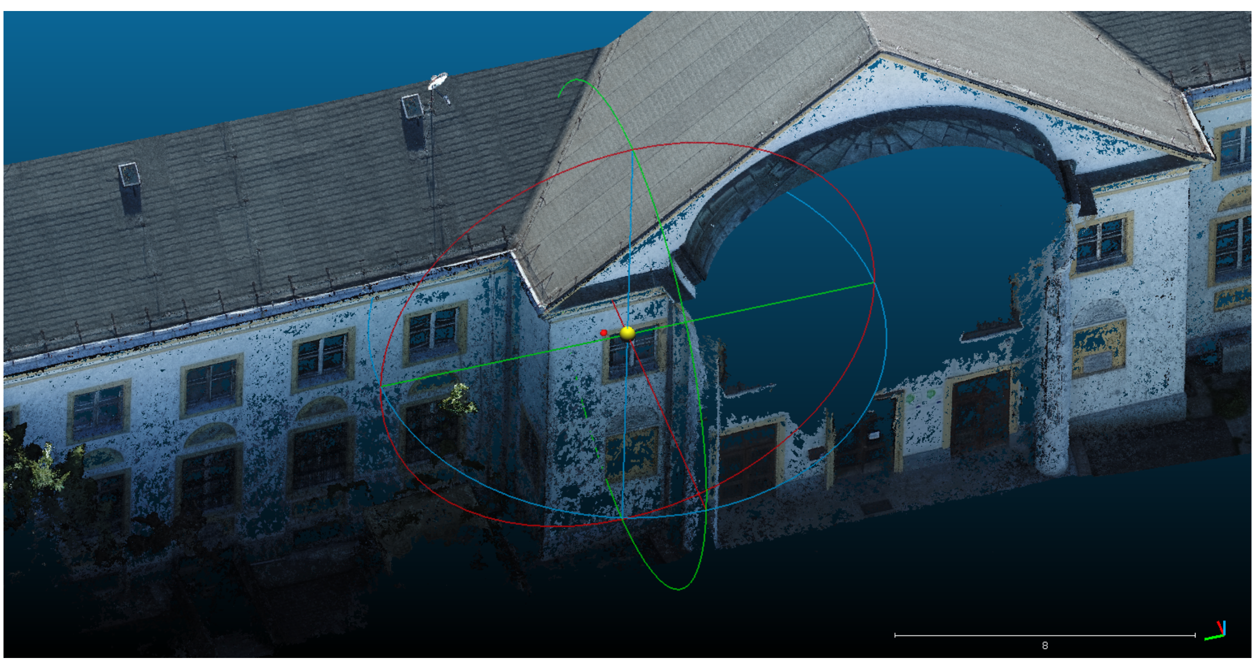

Figure 18. The sectioned focus area of the western facade of the building

The two figures above show the western facade with and without sectioning. The area that has not been caught by the UAV is visible in both images. It is mostly concentrated in the central part of the building.

5.3. Building’s exterior survey with Leica P40 ScanStation static laser scanner

Leica P40 ScanStation static laser scanner performed an extensive survey of the building’s exterior. The instrument was set out at predetermined stations around the building. The survey offers a thorough representation of the facade of the building, with great coverage and density. The point cloud can be observed in RGB, Scalar Field, and other models.

The figure below shows that the external walls and the entire facade, including columns, windows, doors, and balconies are represented in detail within the point cloud. It also features the area that was not identifiable in the DJI Phantom 4 Pro point cloud. The reason for this is that the survey using the static laser scanner was done from the ground, which provided more convenient angles into the behind of columns

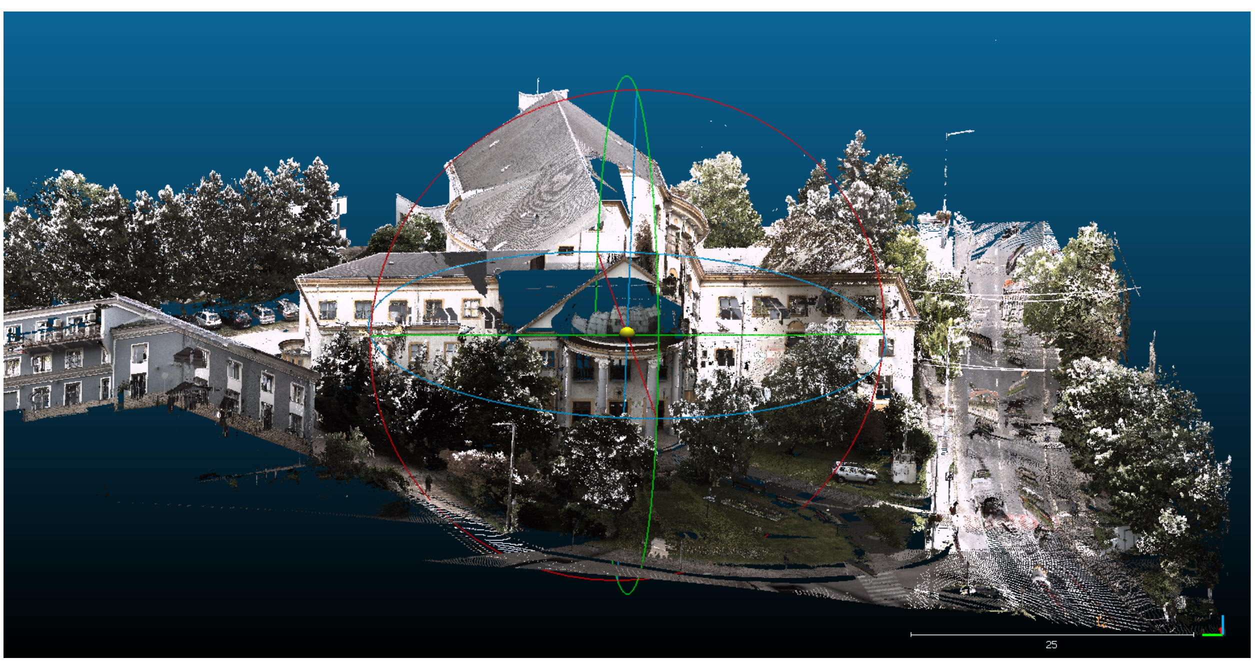

Figure 19. The exterior of the building as seen in the Leica P40 ScanStation point cloud (RGB).

Some parts of the pitched roof are also visible. However, the majority of the roof is still not featured in this survey, while some parts of the included roof segments are not as well-detailed as the facade.

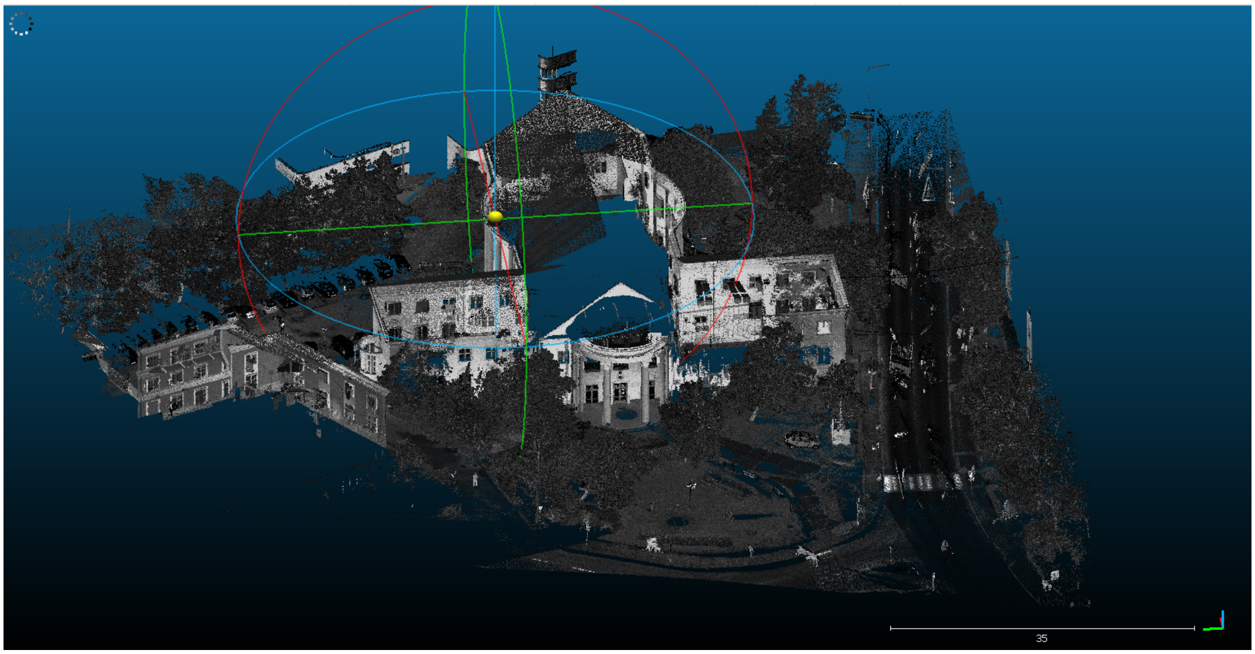

Figure 20. The exterior of the building as seen in the Leica P40 ScanStation point cloud (Scalar Field)

The figure above better demonstrates the contrast between the detailing of the roof and the rest of the building's exterior. Because of this, 4 points (17,18,29,30) could not be located in this point cloud. All of them are located in different parts of the west-facing pitched roof. In contrast, these points were perfectly visible in the UAV point cloud.

It is worth noting that the highest point of the survey was easily located in the Leica P40 ScanStation point cloud. The tipping point of the gable roof, above the front-facing dome, can be well-sighted in the given point cloud. This point cloud also features the terrain, greenery, road infrastructure, and some adjacent buildings.

Table 6. Dataset from Leica P40 ScanStation static laser point cloud

Point ID	X	Y	Z
1	581484.2389	206823.2141	165.902512
2	581484.1561	206820.1966	165.184464
3	581484.2001	206818.1749	165.20253

4	581484.1461	206816.952	165.146866
5	581484.1948	206814.8499	165.151749
6	581484.3381	206811.6042	165.183975
7	581484.5164	206810.0456	165.895187
8	581483.5034	206825.4014	171.66835
9	581483.8026	206815.9264	178.423019
10	581484.0948	206823.3122	169.785812
11	581457.0184	206820.9236	166.878098
12	581459.2619	206818.3752	168.165207
13	581483.634	206819.9312	168.166885
14	581483.7099	206816.7017	166.982315
15	581483.7658	206815.1065	168.139542
16	581484.2589	206815.0289	169.819733
17	NaN	NaN	NaN
18	NaN	NaN	NaN
19	581486.29	206826.5075	169.897095
20	581486.3181	206826.4099	166.512375
21	581482.9901	206811.4693	170.343643
22	581479.6227	206812.9246	170.375656
23	581479.1471	206813.8215	170.356125
24	581487.1334	206791.0266	169.925049
25	581487.093	206792.8493	169.949112
26	581487.0462	206794.2097	169.906982
27	581487.013	206796.1113	169.886475
28	581498.8256	206797.648	169.914261

29	NaN	NaN	NaN
30	NaN	NaN	NaN

5.5. Measurements of the building's interior with Leica BLK2GO Handheld Imaging Laser Scanner

The wireless handheld laser scanner surveyed the entire interior of the building within a short time frame of 2 hours. The Point Cloud features a detailed representation of all floors of the building, including the basement, big and small spaces. The distances chosen for this research were measured using Cloudcompare's "measure" tool, which allows for distance measurements between any two points.

Figure 21. Section of the first floor of the building as seen in the Leica BLK2GO point cloud(RGB)

Precisely locating specific points in the interior of the building can be difficult without having a better sight of relevant areas. That is why the sectioning tool was heavily used during distance measurements in the point cloud. Several sections were made to reach certain points and measure distances, as shown in the examples below.

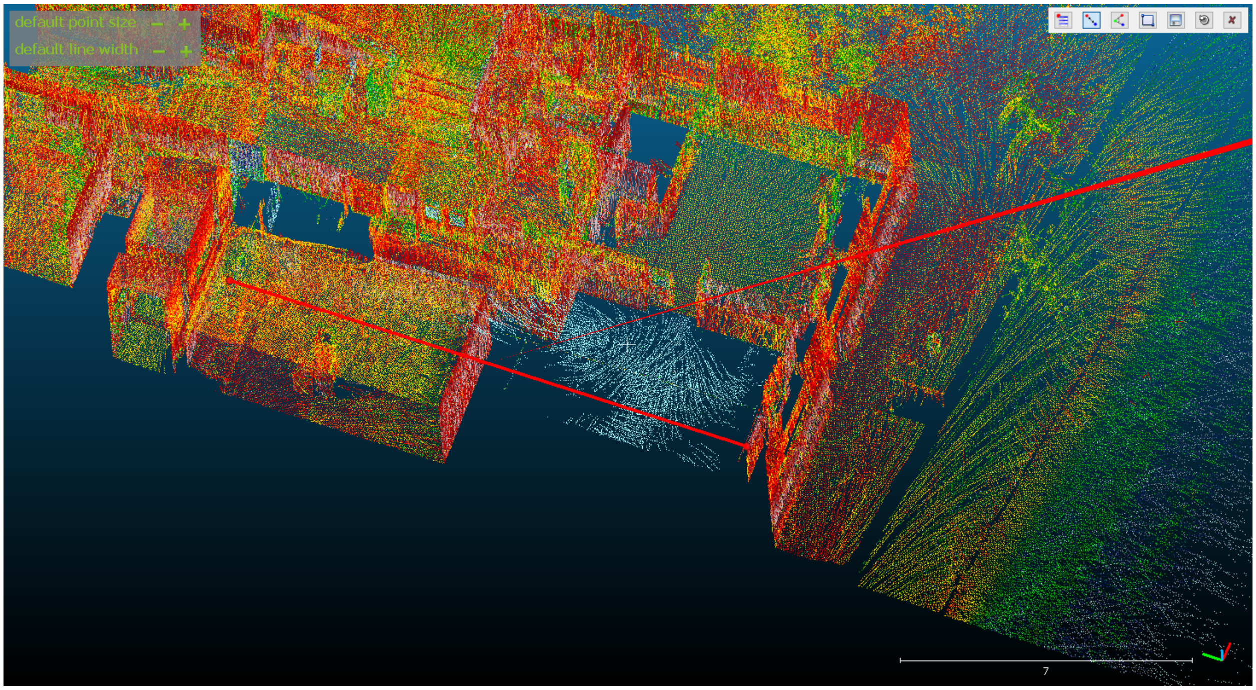

Figure 22. Horizontal section of the upper ground floor for measuring the length of one of the rooms(High contrast)

Distinguishing between points can be challenging in such dense point clouds. Therefore, good use of various color gradient options was made. High contrast, intensity-based representation of the point cloud is of great aid during distance measurements.

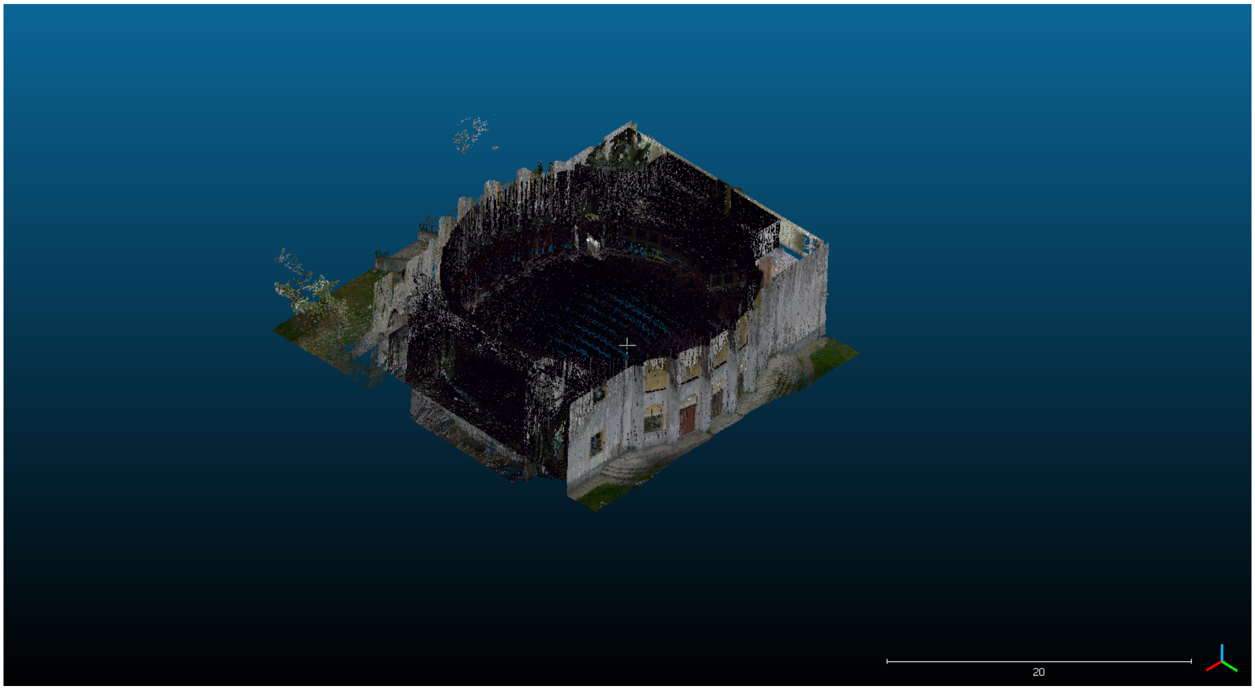

Figure: The isolation of the cinema/concert hall in the building(RGB)

When needed, certain parts of the building were completely isolated using the section tool in order to measure distances more accurately. This method has been particularly beneficial while observing the theater hall in the building. This large space includes numerous minor details, curved shapes, seats, a stage, and a particularly high ceiling.

The interior height measurement in the point cloud was also performed using sectioning and more contrastive color models. The vertical section was used to precisely locate the points in the cloud. It is worth noting that measuring ceiling heights in Cloudcompare requires checking the chosen points from various angles. Therefore, horizontal sectioning might also be required along with slicing the building vertically. In the example shown below, the section was rather clear and points that needed to be selected were in sight, easy to locate and pick.

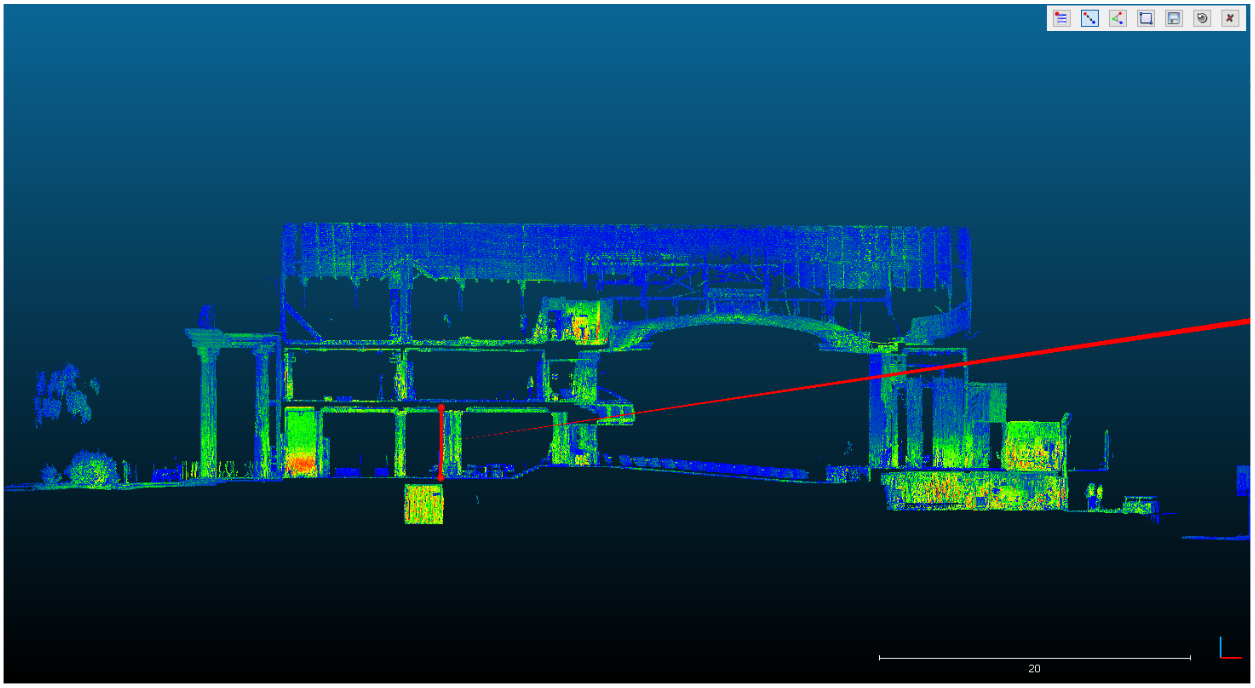

Figure 24. The vertical section of the building as seen from the southern side

The measured column is located on the first floor, near the staircase. The column was isolated in order to measure the diameter.

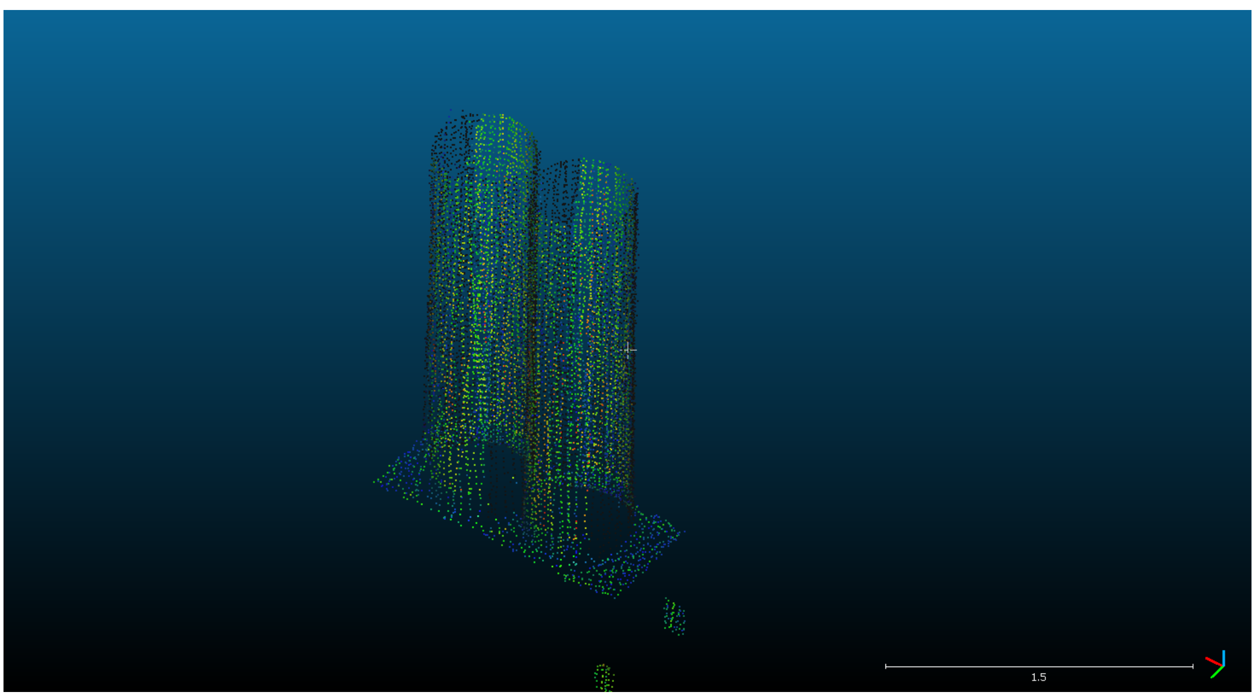

Figure 25. The isolated columns

Subsequently, the diameter was measured using Cloucompare's "measure" tool. The value of the diameter is 52.8915, Hence, the difference between the said number and the diameter calculated from the circumference is 1.16 centimeters. The circumference of the column calculated from the diameter observed in the point cloud is 166.1635478.

Table 7. Dataset derived from the Leica BLK2GO Handheld Imaging laser scanner point cloud

Distance ID	Measurement in meters (Leica BLK2GO point cloud)
1	2.160723
2	4.960511
3	13.302676
4	3.122917
5	20.36034
6	7.329783
7	17.02384
8	8.009841
9	21.89521
10	5.630835

6. Errors

Since one of the goals of this study is to determine the accuracy of point cloud technologies, having precisely surveyed reference points is of utmost importance. However, various obstacles resulted in errors that have shifted our understanding of comparative analysis in this field, while offering a whole new perspective on the possibilities of this research. This chapter explores the errors observed during the process of measurement on the field and in software.

6.1. Gross Errors related to total station's Direct Reflex mode

As mentioned in previous chapters, Trimble M3 3" total station is equipped with the Direct Reflex mode. Surveying the reference points chosen on the facade of the building implied having a clear sight over them. As a result, the direct reflex mode was chosen as a way to cover the most interesting areas of the building.

Reference points were surveyed from two stations. Although all points are located on the west-facing facade of the building, they have vastly different positions. Many of the points are inner corners of window and door frames.

The direct reflex mode has lower accuracy and range than the standard prism surveying mode. The precision of measurements highly depends on the intensity, i.e. strength [Beshr and Abo Elnaga, 2011] of the laser pulse. In the case of inner corner points, as well as the balcony corners and certain parts of the roof, the surface might have reflected the beam more than once. More generally, the reflection angle has shifted from where it was originally meant to be.

Another obstacle with measurements made in Direct Reflex mode is the general tendency of rapidly increasing errors. Several studies have found that such measurements often have higher errors [Beshr et al., 2015] than noted in specifications.

Furthermore, some research works have also cited the importance of the angle of incidence in executing accurate surveying measurements with direct reflex mode. The precision of the survey highly depends on the angle of incidence. The error skyrockets as the aforementioned angle start to exceed 30 degrees [Coaker, 2009].

Only a few reference points on the facade of the building are placed in a way that creates a perpendicular or near-perpendicular angle. Most of the points have higher angles of incidence than 30 degrees. This might have further contributed to the vast inaccuracy of some part of the data from the Trimble M3 3” total station.

As a result of the errors listed above, much of the data had to be taken out of consideration during the accuracy and reliability study. However, they are still present within this paper to emphasize the importance of choosing the right technology for comparative analysis. Also, many aspects of these findings are planned to be taken into consideration in future test measurements.

6.2. Random Errors related to point-picking in the point cloud

Navigating the point cloud can be challenging with dense datasets featuring hundreds of millions of points. Ensuring accuracy when making measurements with this technology is important, yet not always guaranteed. Even with modern software with incredible capabilities, and useful tools, human error remains present when simply trying to pick the right point.

All precautions were exhausted to reach the highest possible precision with point cloud measurements performed for this research. Nevertheless, this kind of error might have contributed to the lack of accuracy in some cases.

7. The data comparison and key findings

7.1. Exterior Measurements

For comparative analysis of the exterior measurements, this research studies the contrast between two types of point cloud technology (Leica P40 Static Laser Scanner, DJI Phantom 4 Pro UAV) and measurements made with the Trimble M3 3” total station. Due to the errors described in chapter 6.1., many of the reference points had to be omitted. They are still featured in the tables below, while more in-depth analysis of large errors and potential causes will be discussed further.

Table 8. Exterior measurements of reference points from the dataset of the Trimble M3 3” total station and Leica P40 ScanStation static laser scanner point cloud

	Trimble M3 3”			Leica P40		
Point ID	**x**	**Y**	**Z**	**X**	**Y**	**Z**
1	581484.026	206823.221	165.912	581484.2389	206823.2141	165.902512
2	581484.099	206820.244	165.212	581484.1561	206820.1966	165.184464
3	581484.159	206818.162	165.211	581484.2001	206818.1749	165.20253
4	581484.162	206816.976	165.173	581484.1461	206816.952	165.146866
5	581484.212	206814.84	165.177	581484.1948	206814.8499	165.151749
6	581484.356	206811.595	165.211	581484.3381	206811.6042	165.183975
7	581484.412	206810.091	165.927	581484.5164	206810.0456	165.895187
8	581483.388	206825.391	171.687	581483.5034	206825.4014	171.66835
9	581483.704	206815.92	178.598	581483.8026	206815.9264	178.423019
10	581484.01	206823.231	169.767	581484.0948	206823.3122	169.785812
11	581484.06	206821.755	169.762	581486.2904	206826.4985	166.878098

12	581484.002	206818.469	168.245	581483.6322	206819.9738	168.16835
13	581484.118	206820.17	168.298	581483.6322	206819.9738	168.16835
14	581484.196	206816.82	167.057	581483.7099	206816.7017	166.982315
15	NaN	NaN	NaN	581483.7658	206815.1065	168.139542
16	581484.254	206815.158	169.657	581484.2589	206815.0289	169.819733
17	NaN	NaN	NaN	NaN	NaN	NaN
18	581491.942	206830.605	176.193	NaN	NaN	NaN
19	581486.182	206826.502	169.912	581486.29	206826.5075	169.897095
20	581486.2	206826.443	166.537	581486.3181	206826.4099	166.512375
21	581482.86	206810.562	170.362	581482.9901	206811.4693	170.343643
22	581479.63	206812.869	170.381	581479.6227	206812.9246	170.375656
23	581479.142	206813.768	170.372	581479.1471	206813.8215	170.356125
24	581487.292	206791.202	169.782	581487.1334	206791.0266	169.925049
25	581487.238	206792.697	169.784	581487.093	206792.8493	169.949112
26	581487.182	206794.383	169.788	581487.0462	206794.2097	169.906982
27	581487.134	206795.872	169.78	581487.013	206796.1113	169.886475
28	581487.086	206797.382	169.935	NaN	NaN	NaN
29	581486.853	206789.01	171.668	NaN	NaN	NaN
30	581489.171	206791.588	173.413	NaN	NaN	NaN

Coordinate values for points number 17, 18, 28, 29, and 30 are not available in the Leica P40 dataset. The reasons for the absence of these reference points located on the roof of the building were discussed before. The window frame that features the point number 28 is also not present in the point cloud. The numbers 17 and 15 are also absent from the Trimble M3 3” dataset, due to the faults related to the recording of the data.

On the other hand, different facade points are missing from the DJI Phantom 4 Pro point cloud. Therefore, it is fair to say that the two-point clouds for the exterior of the building create a single, combined output, that balances the imperfections in each one of them. The points that are unavailable in one are present in another.

Differences in coordinate values of all points (except for the two points not recorded by the Trimble M3 3” Total Station) will be compared with one another. Considering the presence of errors mentioned above, no threshold for accuracy is taken into account, except for the differences in values that are clearly great. Such points are considered to be outliers, in which cases the source of the error will be analyzed and discussed.

If the differences in value for a certain point coordinate are big in the case of both the UAV and Leica P40 point clouds, it is assumed that the measurement made with the total station is not accurate. All other delta values can be subject to further discussion.

Table 9. Exterior measurements of reference points from the dataset of the Trimble M3 3” total station and DJI Phantom 4 Pro point cloud

	Trimble M3 3”			DJI Phantom 4 Pro		
Point ID	**x**	**Y**	**Z**	**x**	**Y**	**Z**
1	581484.026	206823.221	165.912	581484.0957	206823.1953	165.892502
2	581484.099	206820.244	165.212	581484.1498	206820.2353	165.196594
3	581484.159	206818.162	165.211	581484.1677	206818.2066	165.223801
4	581484.162	206816.976	165.173	NaN	NaN	NaN
5	581484.212	206814.84	165.177	581484.2684	206814.8421	165.187195
6	581484.356	206811.595	165.211	581484.3253	206811.626	165.197403
7	581484.412	206810.091	165.927	581484.3911	206810.0575	165.870895
8	581483.388	206825.391	171.687	581483.4568	206825.3581	171.654007
9	581483.704	206815.92	178.598	581483.7749	206815.9248	178.592896
10	581484.01	206823.231	169.767	581484.0981	206823.3261	169.879898
11	581484.06	206821.755	169.762	581484.1237	206821.6075	169.874405
12	581484.002	206818.469	168.245	NaN	NaN	NaN
13	581484.118	206820.17	168.298	NaN	NaN	NaN

14	581484.196	206816.82	167.057	NaN	NaN	NaN
15	NaN	NaN	NaN	NaN	NaN	NaN
16	581484.254	206815.158	169.657	NaN	NaN	NaN
17	NaN	NaN	NaN	NaN	NaN	NaN
18	581491.942	206830.605	176.193	581492.1595	206826.619	176.259003
19	581486.182	206826.502	169.912	581486.2869	206826.4832	169.852905
20	581486.2	206826.443	166.537	581486.3055	206826.3958	166.528397
21	581482.86	206810.562	170.362	581482.8258	206810.5834	170.345306
22	581479.63	206812.869	170.381	581479.642	206812.8949	170.369995
23	581479.142	206813.768	170.372	581479.1557	206813.8039	170.362
24	581487.292	206791.202	169.782	581487.132	206791.0522	169.895905
25	581487.238	206792.697	169.784	581487.0784	206792.8128	169.892105
26	581487.182	206794.383	169.788	581487.0442	206794.223	169.875107
27	581487.134	206795.872	169.78	581487.0031	206795.9903	169.882095
28	581487.086	206797.382	169.935	581486.9623	206797.3753	169.905594
29	581486.853	206789.01	171.668	581486.634	206789.0128	171.632599
30	581489.171	206791.588	173.413	581492.9249	206795.5719	176.239304

The differences in points' coordinates are coordinated by subtracting the total station measurements from either the UAV or static laser scanner coordinates.

The total of 2 points(Points number, 11, 12,) had major coordinate differences of over 1 meter in the Leica P40 dataset. These outliers are not taken into account when comparing data for the purpose of understanding the accuracy, efficiency, and reliability of point cloud surveys. Rather, the 2 points are assumed to have major errors due to identification problems or major differences in the point of reflection in the case of the DR mode measurements of the total station, e.g. instead of the balcony railing, it was reflected from the wall behind. . Therefore, amid the lack of precision, the calculation of reliable values for coordinate differences is impossible.

In the same instrument's point cloud, 15 of the reference points have inaccuracies of over 10 centimeters, but not exceeding 1 meter, in at least one of their coordinates. These points and their coordinates can be evaluated within the framework of comparative analysis. According to the measurement conditions, the clearly identifiable points of the facade often have potential places of multiple reflections, e.g. at corners of the window, the signal may reflect from the glass or the frame, but can also bounce from one surface to the other.

9 points have accuracies of under 10 centimeters. Thus, these measurements are classified as accurate in the dataset. 4 roof points, as well as point number 28 were not included in the Leica P40 point cloud are naturally absent in the comparative analysis of the data.

Table 10. Differences between the coordinates of reference points from the Trimble M3 3" total station dataset and the Leica P40 point cloud.

Point ID	DX	DY	DZ
1	0.2128920001	-0.006932999997	-0.009488
2	0.05714299995	-0.04745000001	-0.027536
3	0.04110400006	0.01287099998	-0.00847
4	-0.01591199997	-0.02395999999	-0.026134
5	-0.01719100005	0.009882999992	-0.025251
6	-0.01786500006	0.009206999996	-0.027025
7	0.104403	-0.04538699999	-0.031813
8	0.115441	0.01038200001	-0.01865
9	0.098597	0.006404999993	-0.174981
10	0.08480299998	0.08116599999	0.018812
11	2.230405	4.74352	-2.883902
12	-0.369836	1.504839	-0.07665
13	-0.4858360001	-0.196161	-0.12965
14	-0.486115	-0.118265	-0.074685
15	NaN	NaN	NaN

16	0.004942000029	-0.129122	0.162733
17	NaN	NaN	NaN
18			
19	0.107978	0.005497999984	-0.014905
20	0.1181150001	-0.033084	-0.024625
21	0.130112	0.907343	-0.018357
22	-0.007318999968	0.055578	-0.005344
23	0.005125000025	0.053529	-0.015875
24	-0.158608	-0.175409	0.143049
25	-0.144982	0.152296	0.165112
26	-0.135842	-0.173313	0.118982
27	-0.1209539999	0.239306	0.106475
28	NaN	NaN	NaN
29	NaN	NaN	NaN
30	NaN	NaN	NaN

The Trimble M3 3” total station surveyed points 1 to 20 from the S1 station. The latter is located roughly in front of the main entrance of the building. Thus, points with smaller angles of incidence were mostly located in the central part of the building, around the main entrance, under the dome.

The tipping point of the gable roof (Point ID: 9) above the dome was also located at a convenient location for the measuring process. However, due to the high elevation and the potential error related to the angle of incidence, the height of the point has been measured grossly inaccurately with the total station.

Some points of the building are spread on the sides of the building’s central entrance section. Additionally, the majority of these points are corners, contributing to the reflection errors described before. As discovered, these conditions create an unfavorable angle for measurements with the Direct Reflex mode. Points surveyed from the S1 station, with IDs 1, 7, 11, 12, 14, 19, all suffered the effects of the circumstances described above, leading to errors in measurements.

The point with the ID 8 is located at the lower corner of the gable roof. The pitched roof of the building's north-western facade is in the background of point number 8. The part of the gable frame is represented in the Leica P40 point cloud, but it is not dense. Moreover, some parts of the frame are still missing from the point cloud. Nevertheless, with the potential high human error of picking the wrong point, the accuracy of the measurement is still high. The only coordinate difference exceeding 10 centimeters is DX, at 0.115441 meters.

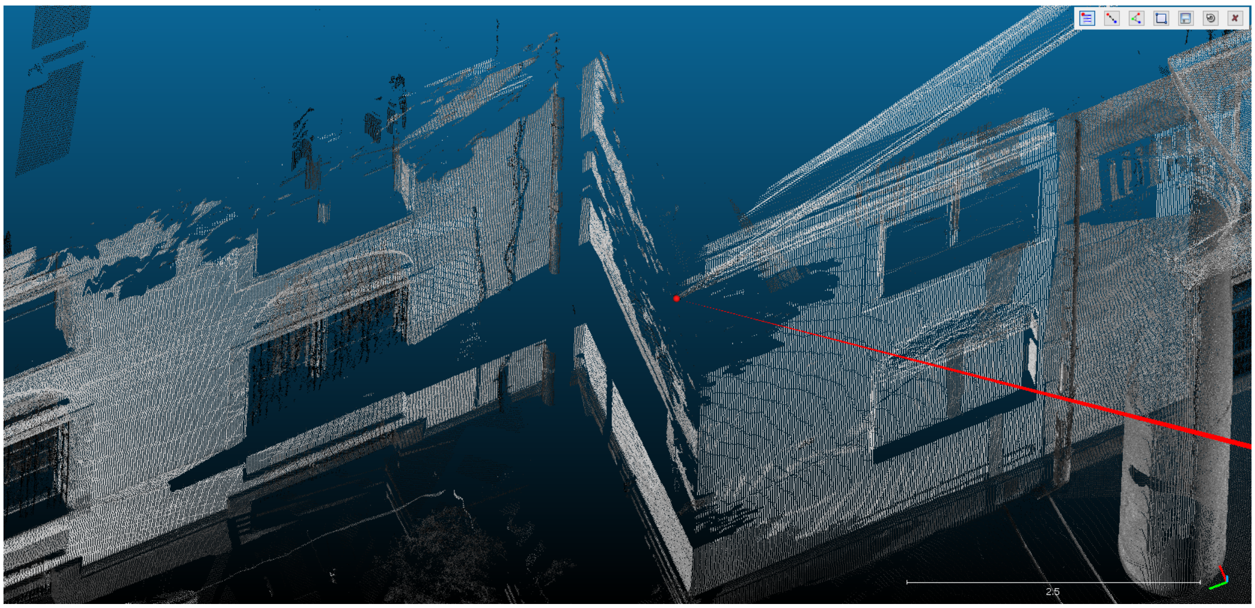

Figure 26. The condition of point 8 in the Leica P40 ScanStation point cloud

Reference points 1 and 7 have similar locations in relation to the central entrance. Moreover, both are disused window frames. Point number is located inside of the frame, in the inner, upper-right corner of the frame. On the other hand, point number 7 is situated on the outer side of the frame, in the upper-right corner.

Figure 27. Illustration of the locations of reference points on the facade of the building, as seen in the Leica P40 ScanStation point cloud (RGB)

When looking at the coordinate differences(DX, DY, DZ), it is clearly visible that the heights of both points were measured with high accuracy. Point number one even has a millimeter precision in the height measurement. Yet, both points have Northing coordinate differences of over 10 centimeters. The DX of point number 1 is 21.3 centimeters, more than twice as high as the same figure from point number 7 - 10.4 centimeters.

Point number 12, located on the corner of the balcony's railing was also severely affected by the error. As the balconies' railings are thin, while having the doors in the background and columns in the front, it is possible that multiple reflections took place in this instance, too.

Point number 11 has some of the highest errors on the dataset. At first, it was assumed that the total station measurement of this point was misleading, affected by errors. However, the same point in the UAV has much higher accuracy. The area around point number 11 has high intensity. Yet, the density of points is low, while the point cloud is missing big parts of the wall. These factors might have led to an error when selecting the point in the point cloud.

Figure 28. The view of the facade that offers a better perspective over balconies and their railings as seen in the Leica P40 point cloud (RGB)

The survey of the points 21-30 was performed from station 23S. These points are located on the right side of the building's west-facing facade, as well as in the centers of the ornaments situated at the top of columns. Points number 22 and 23, located on ornaments, had minor, acceptable coordinate differences. They were easy to sight from the station S23, while the shape of these objects provided a great surface for reflection.

Points 29-30, belonging to the roof, are not detectable in the Leica P40 point cloud. Therefore, they are not featured in the table. Points 24-28 are placed on the first-floor window frames. All of them showed small coordinate differences in comparison to the data collected from the point cloud. However, they are not small enough to be considered completely acceptable.

The location of these points and their correlation with the station S23 has almost certainly resulted in bigger angles of incidence. However, this might not be the only reason why measurements on this part of the facade show a systematic inaccuracy.

The intensity of the point cloud in this area of the exterior might have further altered the measurements. In this instance, the error could have affected the Leica P40 point cloud survey. The intensity distribution across the facade of the building clearly outlines the area, where points 24-27 are located, as having significantly lower intensity points than other parts. The lack of high-intensity points is often in direct correlation with the point cloud noise [Bolkas, D. & Martinez, A. (2018)].

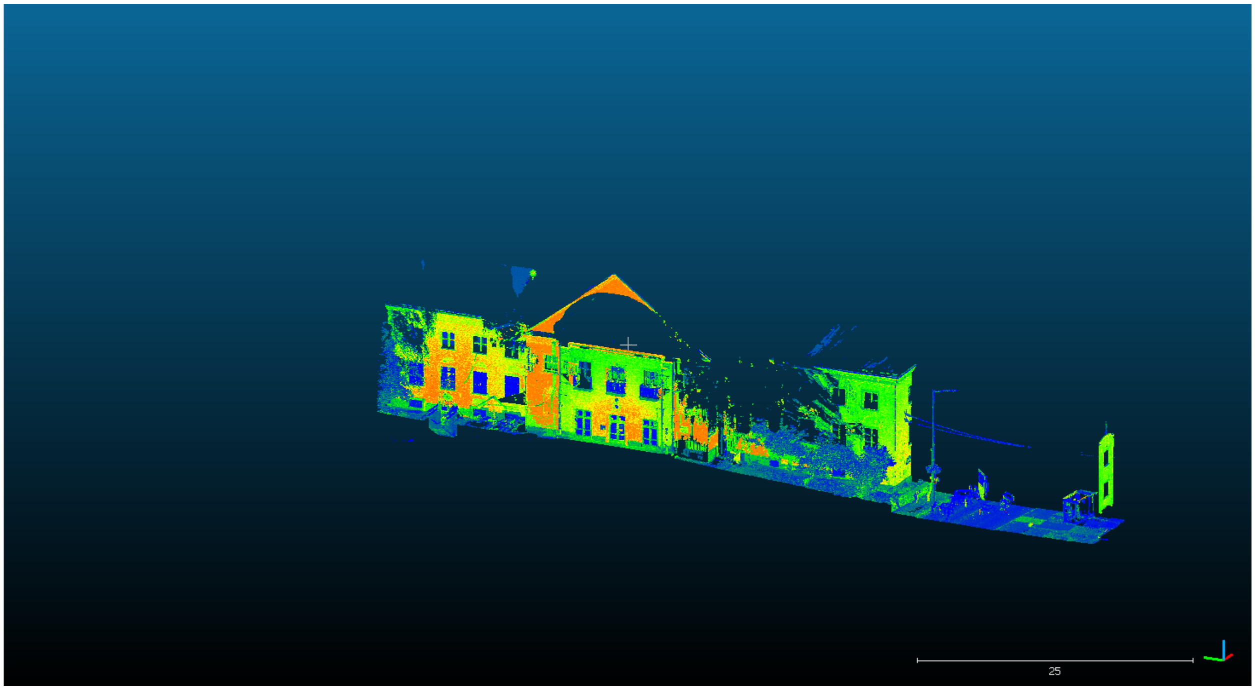

Figure 29. The intensity distribution across the west-facing facade of the building. (Blue indicating the lowest and red the highest intensity)

The figure above illustrates the distribution of intensity particularly well. The entire southern wing of the facade is characterized by lower intensity (green) points. Such a disposition of intensity could be a result of a longer measuring range from green and blue areas to the laser scanner.

Taking into account the low intensity of points 24 to 27 along with their angles of incidence, the resulting errors can be explained. It is important to acknowledge that all of these points are situated on the same level of the building. Moreover, they are all upper corners of windows. Being mindful of the latter, the minor differences between DXs, DYs, and DZs appear to be more sensible. Therefore, it can be said that if the two main types of errors were eliminated from these measurements, the data from Leica P40 ScanStation for points 24-27 would have been highly accurate.

The importance of high-intensity point cloud data can be further elucidated with an example of points 2-6. All of these reference points are located on the ground floor door frames. They have a small elevation difference with the instrument and a lower angle of incidence. Therefore, the total station survey of these reference points was not affected by errors highlighted in this research.

Importantly, the area around these points has a significantly higher intensity, with the vast presence of yellow and red points. As a result, the accuracy of points 2-6 are very precise. Mean values for DX, DY, and DZ are low, further demonstrating the precision of this part of the survey.

Table 11. Mean values and standard deviations for DX, DY, DZ values of points 2-6

Coordinate differences	**Mean Value [m]**	**Standard Deviation [m]**
DX	0.02984	0.0166
DY	0.0207	0.0144
DZ	0.0229	0.0072

Based on Table 11, the accuracy along a coordinate axis is ±2.0-3.0 cm, resulting in a spatial accuracy of the point cloud information is ±4.19 cm, which is acceptable in case of not too high accuracy demand.

Considering different parts of the building and reference point data discussed above, a reckoning can be made about the overall accuracy of the Leica P40 Scan station static laser scanner point cloud. If the errors that occurred in the surveying process of the Trimble M3 3” total station are disregarded, the point cloud can be considered to be accurate for some centimeters. With points affected by low intensity and big angles of incidence (e.g. Points 24-27), despite the presence of errors, there are homogeneous differences between DX, DY, and DZ. This allows for the assumption that the point cloud is precise.

The DJI Phantom 4 Pro UAV point cloud and Trimble M3 3” coordinates were much more aligned, as can be seen in the table below. The coordinate differences are smaller and there are only two outliers - points number 18 and 30. Point number 30 is located on the southwestern part of the roof. It is a corner point and with a high elevation. The measurement of the said point with a total station was most likely affected by errors. Point number 18 is located in a similar area but on the opposite side of the roof.

11 points have coordinate differences above 10 centimeters, yet, not exceeding 21.9 centimeters. Overall, at a global scale, the DJI Phantom 4 Pro point cloud seems to be giving a much more accurate, finalized picture of the reference points measurements.

Table 12. Differences between the coordinates of reference points from the Trimble M3 3" total station dataset and DJI Phantom 4 Pro UAV point cloud

Point ID	DX	DY	DZ
1	0.06969999999	-0.02570099998	-0.019498
2	0.05079999997	-0.008700000006	-0.015406
3	0.008700000006	0.04459999999	0.012801
4	NaN	NaN	NaN
5	0.05639999988	0.002100000012	0.010195
6	-0.0307	0.03099999999	-0.013597
7	-0.0209	-0.03349999999	-0.056105
8	0.06880000001	-0.03289900001	-0.032993
9	0.07089999993	0.004799999995	-0.005104
10	0.08809999994	0.095099	0.112898
11	0.06369999994	-0.1475	0.112405
12	NaN	NaN	NaN
13	NaN	NaN	NaN
14	NaN	NaN	NaN
15	NaN	NaN	NaN
16	NaN	NaN	NaN
17	NaN	NaN	NaN
18	0.2174999999	-3.986001	0.066003
19	0.1048999999	-0.01880000002	-0.059095
20	0.1055000001	-0.0472	-0.008603
21	-0.03419999999	0.0214	-0.016694
22	0.01199999999	0.02590000001	-0.011005
23	0.01370100002	0.03589999999	-0.01

24	-0.16	-0.1498	0.113905
25	-0.1596	0.1158	0.108105
26	-0.1378	-0.16	0.087107
27	-0.1309	0.1183	0.102095
28	-0.1237	-0.006699999998	-0.029406
29	-0.218997	0.002799999987	-0.035401
30	3.753896	3.9839	2.826304

The UAV point cloud does not feature 5 reference points. These are points number 4, 12, 13, 14, and 16. The reason behind the absence of these points is simply a large area of the west-facing facade that is not covered by the DJI Phantom 4 Pro survey.

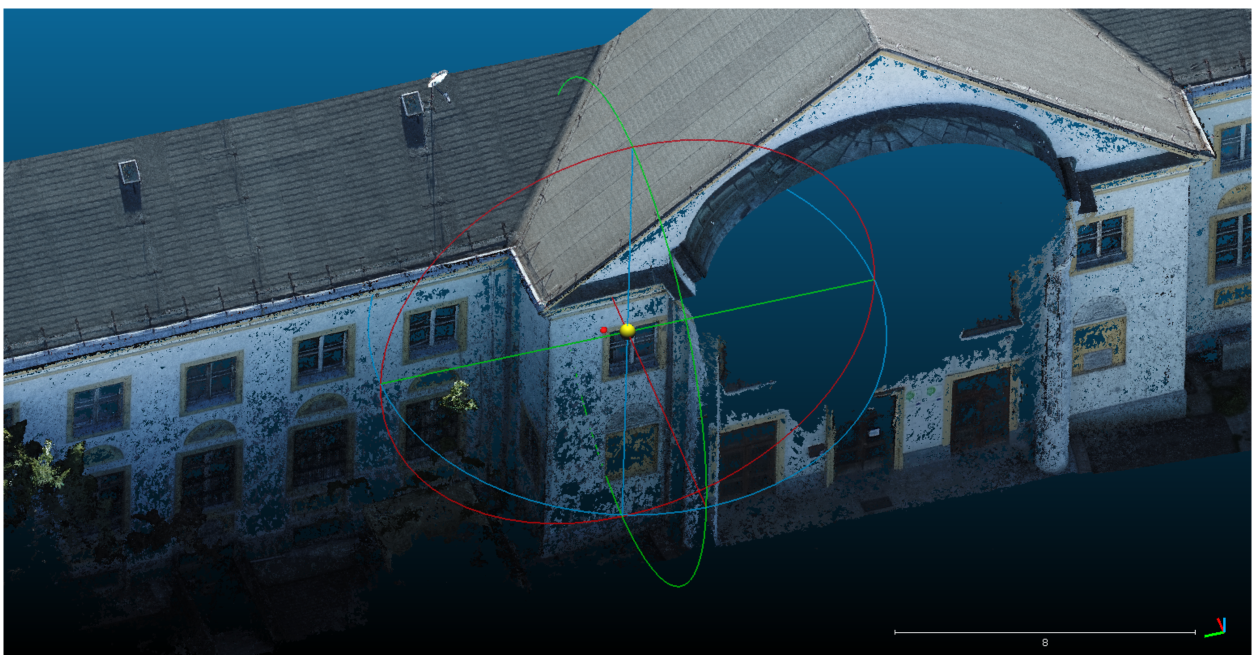

Figure 30. The DJI Phantom 4 Pro point cloud is missing an important part of the facade located under the dome. The building was sectioned for a better perspective over the absent parts.

On the other hand, points 1 to 9 have acceptable accuracy. In the case of the UAV point cloud, there is no error with the Northing coordinates of points 1 and 7 either, unlike in the case of the Leica P40 point cloud. Yet, point number 4 is excluded from the dataset since it has not been covered by the survey.

Table 13. Mean values and standard deviations for DX, DY, DZ values of points 1-9 (excluding point number 4)

Coordinate differences	Mean Value [m]	Standard Deviation [m]
DX	0.0471	0.0226
DY	0.0229	0.0147
DZ	0.0207	0.0154

The mean values and standard deviations of coordinate differences for points 1-9 (excluding point 4) is in the range of some centimeters, as per expectations. The highest mean value is recorded for the Northing coordinate differences. Yet, it is still under 5 centimeters. The mean values height and Easting coordinate differences are both under 2.3 centimeters. Based on Table 13, the spatial mean error is ±5.63 cm, which is acceptable, particularly due to the fact that in this case apart from some obvious outliers (to be discussed also in the next paragraphs), not much filtering of the data was performed before the statistics have been determined, e.g. 8-9 cm coordinate errors at points 3 and 10 are included in the statistics.

The two outliers are both situated on the roof of the building. Point number 30 is an intersection of the two hips and the ridge. The area is easily detectable since it is a corner point on the roof. The chances of picking the wrong point are low since the surface area of the corner is small and the point cloud on the roof is dense. Considering that this is the UAV point cloud, the roof is expected to have some of the most intense and dense points. Taking into account the high accuracy of the DJI Phantom 4 Pro with the previously discussed points, the roof survey can also be considered precise. The high error in the measurement of point 30 is likely caused by faults in surveying the total station. Therefore, this point can be considered an outlier.

Point number 18 is another outlier. It is located right under the roof ridge, at the bottom of the support for the wiring that runs along the ridge. On one hand, there can be an error related to the measurement made with the total station. The part of the ridge the point is situated in is thin. On the other hand, the support for the wiring, as well as the wire itself are barely visible in the UAV point cloud. The shapes have a lot of noise and are blurry. Therefore, it is very difficult to choose the right point.

The coordinate differences for point number 18 are generally inaccurate. Yet, the error in height is only just over 6 centimeters, while the Northing coordinate is off with the coordinate difference of 21.7 centimeters. Although not highly precise, these measurements could have still been considered in some way accurate, if not the major 3.986-meter error in the Easting direction. Considering the accuracy of the height measurement, the assumption can be made that the location of the point was chosen wrongly, mainly along the ridge.

Interestingly, points 24-27 follow a very similar pattern to the data for the same points from the Leica P40 point cloud. Their inaccuracies range from 10 up to 16 centimeters. There are no obvious outliers among these points. Worth noting, DX values for these points decrease from point 24 to point 27 in both point clouds. Yet, overall, the coordinates taken from the UAV point cloud seem to have smaller differences with the total station data.

These findings further illustrate the fact that the survey of points 24-27 made from station point S23 was affected by errors related to the angle of incidence and possibly the low intensity of points. If these effects were eliminated, both the UAV and the static laser scanner cloud point data for these points might have been considered accurate.

7.2. Interior Measurements

The reference distances chosen for this research were measured with the Leica Disto D5 mobile measure and compared to the same distances taken from the Leica BLK2GO handheld imaging scanner. As mentioned before in this study, the distances were taken in a diverse range of spaces to accurately reflect on the capabilities of the scanner.

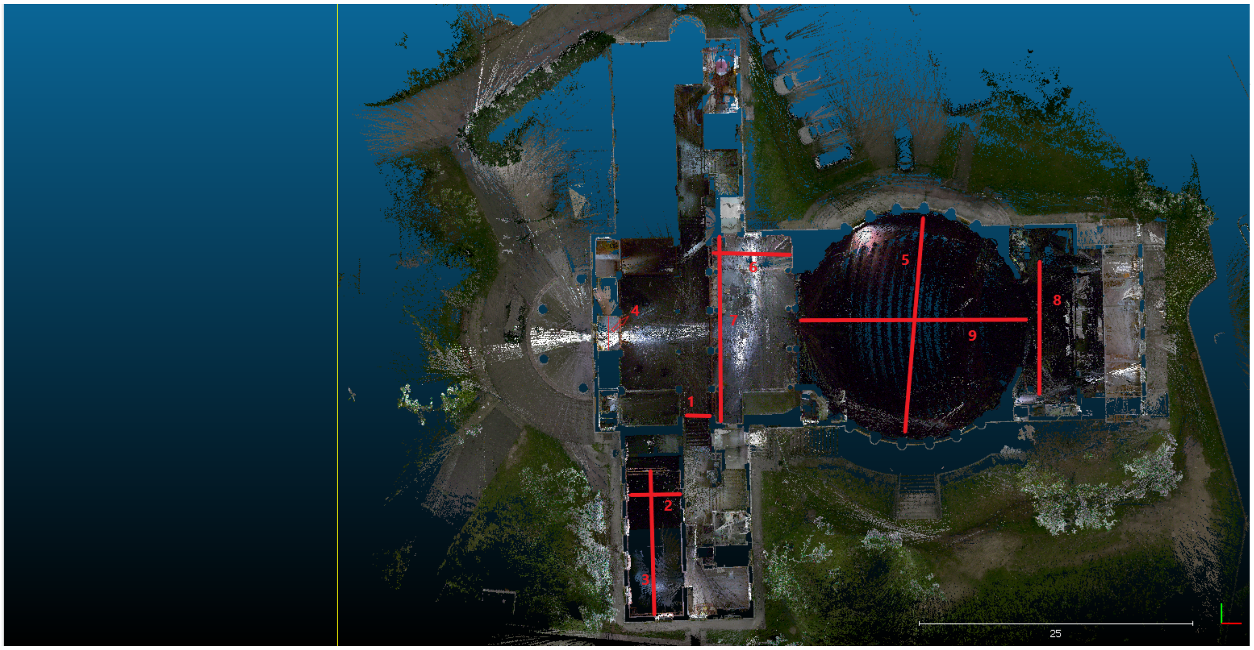

Figure 31. The ground plan of the building's ground floor is seen in the Leica BLK2GO handheld imaging scanner point cloud. Distances are denoted with numbers.

In the case of distance measurements, the error of picking the wrong point in the software is partly eliminated. Most measurements are performed between two even-surface walls. In such an instance, the vertical section of the relevant part of the building is of great help. Choosing the right height is significantly easier in a vertical section, while the horizontal position can be pre-arranged as the cutting point when slicing the building.

However, some walls are curved and spaces, such as the theater hall in this building, are rather big in scale. The comparative analysis of distance measurements performed by Leica BLK2GO and Leica Disto D5 showed an interesting, yet anticipated picture.

Table 14: Distance measurements and differences. Measured with Leica Disto D5 and Leica BLK2GO.

Point ID	Leica Disto D5 [m]	Leica BLK2GO [m]	Differences [m]
1	2.168	2.160723	0.007277
2	4.963	4.960511	0.002489
3	13.343	13.302676	0.040324
4	3.125	3.122917	0.002083

5	20.503	20.36034	0.14266
6	7.323	7.329783	0.006783
7	17.035	17.02384	0.01116
8	8.001	8.009841	0.008841
9	21.76	21.89521	0.13521
10	5.627	5.630835	0.003835

Overall, distance measurements in the point cloud have proven to be highly accurate. The millimeter precision was observed in 6 reference distances, highlighted in green in the table above. The mean difference for the aforementioned 6 points is 5.22 mm, while the standard deviation stands at 2.55 mm.

The 2 points highlighted in yellow had a centimeter precision in distance measurement. The higher error among the 2 was detected in the reference distance number 3. This measurement deals with the length of the ballet room located on the upper ground floor of the building. The room has a large mirror wall on one of the sides of the length. This could be the reason why the said wall is not dense and very clear in the point cloud. Nevertheless, the distance measurement bearing a potential error is still possible.

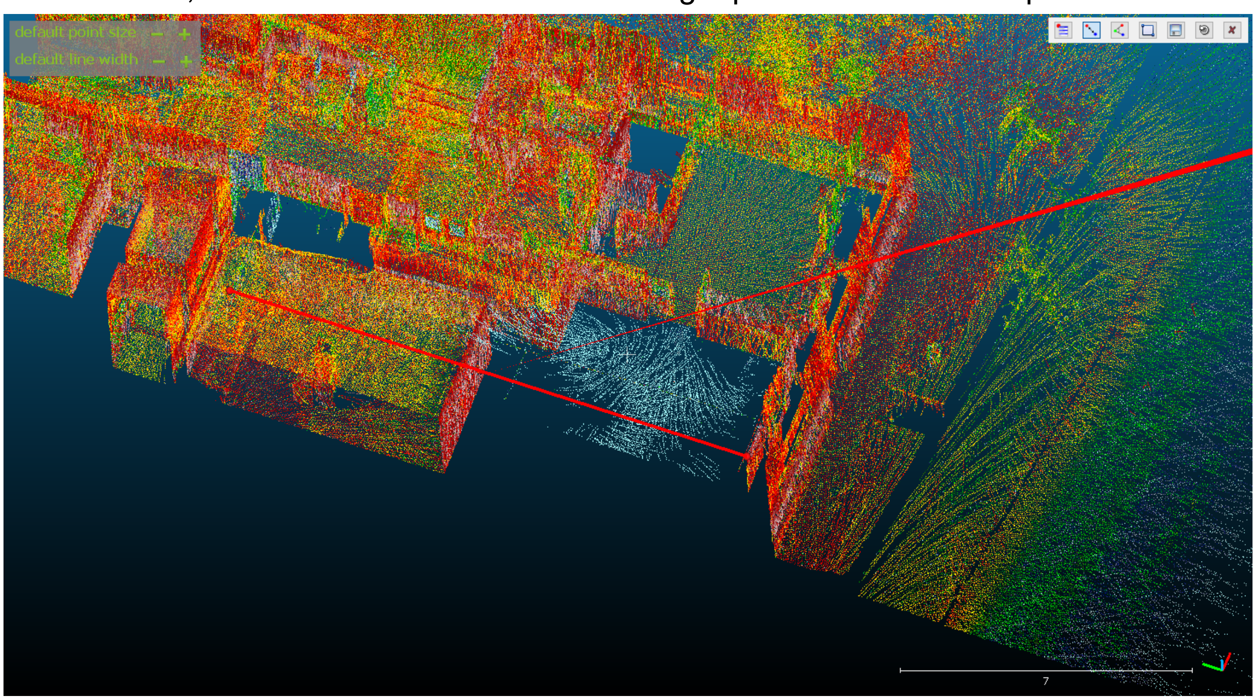

Figure 32. The ballet room and the measurement of the reference distance 3 as seen in the Leica BLK2GO imaging scanner point cloud (High Contrast)

One other factor that can already be observed based on the 8 points discussed is the size of the distance. All 6 highly accurate measurements are dealing with distances smaller than 10 meters. On the other hand, the two measurements with lower accuracies occurred on distances of approximately 13.3 and 17.0 meters.

Large distances affect measurements in more than one way. The impact of long-range scanning in big spaces became apparent during the intensity analysis of the interior point cloud.

The more spacious the room, the lower the intensity of points is. This phenomenon is best visible in the theater hall, which consists of almost only low-intensity points. On the contrary, smaller rooms, hallways, and lavatories have far more intense point sets.

Unsurprisingly, the lowest accuracy distance measurements on the dataset are both recorded in the theater hall. This large space not only has significantly lower accuracy points but also features a curved shape, which can affect the accuracy of measurements. Furthermore, these distances were measured between (seemingly) flat surfaces, and no actual point on these surfaces could have been identified, accordingly, the more than 10 cm difference may also arise from the difference of the place of measurement at the site and in the software.

A very important message of the interior test measurements is that the handheld laser scanner proved to work with high accuracy, no such outliers were detected than in the case of the exterior facade. Accordingly, the use of handheld laser scanners is highly recommended due to their accuracy performance and their convenient and quick use.

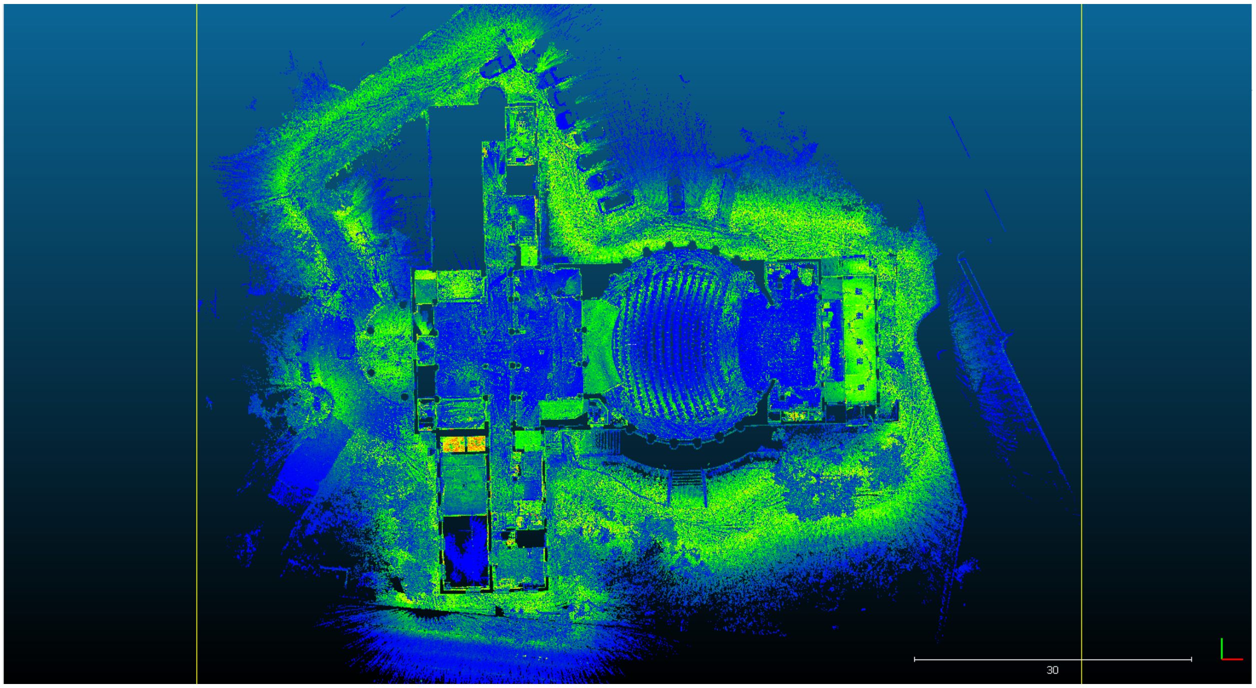

Figure 33. The intensity distribution across the ground floor of the building, as seen in the Leica BLK2GO point cloud.

8. Conclusions

Initially, the prime goal of this research work was to evaluate the accuracy, efficiency, and reliability of point cloud technologies in surveying with a particular emphasis on the most recent handheld laser scanning technology. As an emerging field, this topic is of utmost importance for keeping up the standards and the entire sector with the technological breakthroughs. However, during the process of analyzing the collected data from both point clouds and traditional surveying instruments, several errors were detected. These findings have led the research in a new direction. This is the reason why some of the conclusions of this paper are related to the explored errors.

The process of surveying large buildings with point cloud technology is incredibly time-efficient. After planning the flight of a UAV, the process of capturing all needed points took only 20 minutes for this building. The static laser scanner requires 10 minutes of measurements per standpoint. Considering the high scan rate capacity of the instrument, (1 million points per second) it can be described generally as an efficient method of surveying. This is particularly true for the handheld laser scanner, with which the whole interior could have been observed in 2 hours, or so.

Emphasizing the importance of errors that have impacted the course of this research work is crucial. There is limited scientific data or resources dealing with the comparative analysis of traditional surveying methods and point cloud technology. Therefore, the preferred ways of surveying reference points with total stations are not universally acknowledged. Considering the scale of the point clouds, the Direct Reflect mode was chosen as an easy and convenient way of surveying reference points with the total station. The latter resulted in some major measurement errors, underlined by factors such as big angles of incidence, multiple reflections, and varied reflection surfaces. Although, several outliers of the static laser scanning, such as outliers along one coordinate axis only could have been detected compared to this reference.

Despite the presence of these errors at some points, an important part of the processed data still proved to be usable for comparative studies. Some points with smaller errors even helped in understanding the potential influence of the point intensity on the accuracy of the point cloud.

Several points had high precision in both the UAV and Static Laser Scanner point cloud datasets. Such points created a good picture of both point clouds' accuracies. For instance, approximately the same range of points had acceptable accuracy in both point clouds. Standard deviations of points 1-9 in the UAV point cloud - DX:0.0226 DY:0.0147 DZ:0.0154. Standard deviations of points 2-7 in the Static Laser Scanner point cloud - DX:0.0166 DY:0.0144 DZ:0.0072 (all in meter unit).

The intensity stood out as an important factor in the point cloud dataset. Considering the scale of the building, the distribution of intensity was not expected to be perfectly equal across its exterior and interior. Nevertheless, all datasets showed that the longer-range measurements result in poor intensity and high noise in point clouds. Various precautions exist to increase the intensity of points in big spaces. These factors are related to specific means of technology, lighting, colors of reflective surfaces, and more. These aspects are not subjects of this study. However, the analyzed data highlights how important the intensity distribution can be.

Distance measurements performed in the point cloud appeared as precise and efficient. Long-distance measurements emerged as a source of minor errors. However, larger errors were not solely caused by long distances, but also as a result of curved shapes of walls and the lack of dense data in the point cloud. Overall, it is fair to say that point cloud distance measurements are accurate and time-efficient.

One more important aspect of the research is the software used for identifying points and their coordinates, measuring distances, and making comparisons. CloudCompare is open-source, free-to-download software that provides a great platform for working with point clouds. Point-picking is accurate and the program features many useful tools, including those dedicated to the statistical analysis of the point cloud. However, there is still a lot of room for improving the interface features that affect the work process. Measuring distances in perpendicular directions can be made simpler, perhaps with the addition of a separate tool.

Point clouds are an incredible technology that can be the future, as well as the present of surveying. The more technologically advanced methods of surveying are efficient while generating insightful 3D representations of buildings. This research, despite difficulties with reference point measurements, has found point cloud technology to be at large accurate.

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