LESSONS LEARNT FROM THE HIGH RESOLUTION UAS PHOTOGRAMMETRIC SURVEY OF A HISTORIC URBAN AREA: UNESCO SITE OF SABBIONETA

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ABSTRACT:

In view of the increasing development of the smart city concept and the generation of 3d city models, it becomes essential to have an up-to-date, high-detail 3D survey of urban areas. There are several technologies that enable the development of a geometric survey of urban areas, including the use of aerial laser scanning, remote sensing, mobile mapping systems, and Unmanned Aerial Sistems (UAS) photogrammetry. Of these, the last mentioned, when developed with high-resolution cameras and flight plans with appropriate elevations, allows point clouds to be obtained at a high level of detail and orthophotos with great resolution. This technique may be the preferable choice when the object of the survey is a historic urban area, which has some special features, which might make surveying difficult with other surveying techniques. This paper presents the survey with UAS photogrammetry of a historic urban area: the city of Sabbioneta, in northern Italy. The UAS flight planning is discussed in details, specifically referring to european UAS flight regulations. The survey was developed with DJI Matrice 300 RTK, equipped with a flight terminator and parachute, and coupled with a high precision GNSS Mobile Station DJI D-RTK 2. Ground control points and check points were measured with GNSS receiver Leica GS18. Images were processed with Agisoft Metashape following a photogrammetric workflow. The resulting orthophoto has a pixel size of 1 cm. The obtained dense point cloud is suitable for future use for its segmentation by testing existing machine learning and deep learning methods and for future urban analysis.

1. INTRODUCTION

The generation of highly detailed 3D city models and the management of smart cities surely benefit from an accurate geometric survey of the city itself. Within this context, the methods for 3D city model production typically involve the combination of 2D cartography (or topographic database) and 3D point clouds (Pađen et al., 2022). Apart from Aerial Laser Scanning (ALS) or Remote Sensing datasets, coupled with cartographic datasets, Unmanned Aerial System (UAS) photogrammetry could be a valuable alternative, exploiting either vertical or oblique images (Oniga et al., 2022, Salas López et al., 2022, Ilić et al., 2022).

The topic of the UAS photogrammetric survey of urban areas is therefore of great interest, both for the technical expedients used and for the purposes and uses of the generated point cloud. The size of the surveyed urban area, and the goals of the survey, drive the choice of the most appropriate technical solutions for the survey, like the type of drone, the camera and its resolution, the quality and mode of image acquisition, the photogrammetric processing parameters, and the georeferencing approach. The resulting UAS photogrammetry point cloud can have a higher or lower density of points, according to the flight altitude and the resolution of the camera used.

Furthermore, considering the point of view of a photograph taken by UAS. it is possible to collect data related to roofs and upper part of facades, which are difficult to be reached using other approaches, like the use of Mobile Mapping Systems (MMS), or TLS. The drawback, on the other hand, is that some parts of building facades, especially in very narrow streets and with tall buildings, are not reconstructed in the point cloud since they are poorly visible in the photos. In order to achieve greater coverage, the survey of urban areas can benefit from the integrated use of surveys from different systems, such as the combination of MMS and UAS photogrammetry (Wahbeh et al., 2022), taking into account the different accuracies of the two systems.

A historic urban area can be effectively considered a complex urban scenario. It generally contains buildings with complex shapes and position, a street axis that tends to be formed by narrow streets with a strong presence of urban canyons, and special urban components such as monuments, fortified walls, monumental gates, etc. In such conditions, in order to develop 3D city models with high level of detail (LOD), or to analyse the survey data to extract useful information, it is often necessary to use a point cloud with high density of points. To do so it is possible to exploit a photogrammetric process, using UAS photogrammetry (Toschi et al., 2017), or the combination of MMS and Aerial photogrammetry (Picon-Cabrera et al., 2021), obviously having varying levels of detail depending on the GSD of the images, and so with regard to the camera characteristics and the flight altitude.

In this context, the purpose of this paper is manyfold. Firstly to carry out a practical application test of the UAS DJI Matrice 300 RTK, mounting a Zenmuse P1 camera. Secondly, the description of the acquisition phases and of the expedients used on the field to enhance the survey process and generate a 1cm GSD orthophoto. Thirdly, the generation of a high point density dataset to reuse for the generation of a 3D city model, and for further tests on segmentation, navigation, representation and modelling purposes, including the implementation of Machine Learning and Deep Learning approaches. In particular, this point cloud could be the starting point for developing and testing the scalability of processing algorithms and procedures designed for non-historic urban areas, and for the creation of new workflows

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more calibrated to a historic urban environment. Lastly, this paper is also the opportunity to describe some aspects related to Italian (and European) UAS flight regulations, with safety procedures. The case study selected is Sabbioneta, a historic city located in Northern Italy.

The paper is organized as follows. In section 2 takes places a description of the instruments used, the case study, the flight plan, and the acquisition phases. Section 3 describes the photogrammetric process and its results, including the generation of the high-resolution orthophoto, and a first analysis of the point cloud. Section 4 is dedicated to a discussion of the survey, the technical expedients implemented, and the photogrammetric results. Section 5 draws out conclusions.

2. THE SURVEY

2.1 Instrument selection

The choice of the most suitable UAS to use for the survey is of great importance both in terms of the quality of the final data (depending on the type and dimension of sensor, and accuracy of the GNSS system) and risk management - an aspect that is always complex in the case of overflying inhabited urban centres-. The survey was conducted with the DJI Matrice 300 RTK. This system guarantees a flight autonomy of more than 45 minutes (55 minutes declared by the manufacturer) and this allows the flight project to be optimised, choosing even large areas and not fragmenting the entire job more than necessary. The DJI Matrice 300 RTK also has a high safety standard due to the already active geofencing, altitude limits, obstacle sensing, and smart Return To Home (RTH) technologies. It also features redundancy of the main systems, so the battery, Inertial Measuring Unit (IMU), barometer, and compass are duplicated and ensure continuity if the primary unit fail. Similarly, the main circuit boards have a backup power supply and communication circuits to promote reliability. The radio remote control is also doubled. The two controllers allow simultaneous control by the two pilots, to separate flight operations (pilot) from photo capture operations (video operator), and allow the two pilots to move independently to cover large distances always maintaining the VLOS (Visual Line of Sight) mode. Finally, to ensure maximum security, the UAS is equipped with a flight terminator and parachute. Table 1 shows some details of the aircraft.

Feature	Description
Dimensions (without propellers)	81 x 67 x 43cm
Max weight to take off	9 kg
Max speed vertical	7 m/s
Max speed horizontal	17 m/s
Autonomy (batteries)	55 minutes
RTK position accuracy (horizontal)	1 cm + 1 ppm
RTK position accuracy (vertical)	1.5 cm + 1 ppm

Table 1. DJI Matrice 300 RTK technical features, retrieved from DJI website.

The UAS is characterized by a high-precision GNSS Mobile Station DJI D-RTK 2. The GNSS mobile station was intended to achieve the aircraft's centimetre-level position accuracy, so each image could be taken together with its geographic position for direct georeferencing.

The UAS mounted a Zenmuse P1 camera, with a full-frame 45 MP sensor of 35.9x19 mm, mounting DJI DL 35mm F2.8 LS ASPH (with lens hood and balance/filter ring), FOV 63,5°.

Control points and check points spread around the city, were measured with Leica GS18 T GNSS RTK rover with Leica CS20 field controller in Network Real Time Kinematic (NRTK) Positioning, leaning on Leica Smartnet Italpos.

2.2 Case study description

The historic urban area selected for the study is Sabbioneta. It is a historic city, built between 1556 and 1591 by Vespasiano Gonzaga following the *Ideal City* principle, theorized during Italian Renaissance. The city is inscribed on the UNESCO World Heritage Site together with the near city of Mantova since 2008. The city is a good example of a perfectly preserved historic urban environment: formed by streets of varying widths, a chessboard pattern with a *cardo* and *decumano*, residential buildings with, on average, two-three floors, two main squares, monuments, bell towers, colonnades, and pedestrian areas. The city has an area of roughly 40,000 square meters, the orography is mainly flat, and the average elevation 18 meters above sea level.

This city was considered appropriate both for testing the selected UAS and for generating an optimal dataset for future studies. Firstly, because it is limited in size but still with different and larger proportions than other typical UAS surveys, such as a single building or an agricultural area. Moreover, the organization of the city presents typical features of a historical area that can be challenging if the goal is to maintain a homogeneous high resolution throughout the survey. Some of these features are fortified walls, gateways with entrance bridges, narrow streets, alleys, arcades, and pedestrian areas.

2.3 Flight planning

Although this was an instrumental test, the goal was to create a high-quality documentation of the historic city centre, either through an orthophoto (immediately usable by the municipality) or through a point cloud (also useful for research). For this reason, all the operations were discussed and agreed with the municipality, which showed its interest in the very high-resolution orthophoto, as a tool for the management of the area. The flight mission involved the Sabbioneta area, which is in a geographic area where the maximum allowed flight altitude corresponds to 45 m. Therefore, the maximum altitude was restricted to this value and, according to the provisions of the Italian National Civil Aviation Authority (Ente Nazionale Aviazione Civile, ENAC), there is no need for authorization to occupy the airspace. The type of mission fell under the procedures outlined in LG-2020/001-NAV - Annex A.1-*Scenario Standard IT-STS-01*. The first element to consider for the flight plan was the Ground Sample Distance (GSD). Considering the full-frame sensor of DJI Zenmuse P1 and the 35° mm lens, and the maximum height constraint, the expected average dimension of each pixel on the ground was about 5 mm. It allowed a very high resolution for both the outcomes (orthophoto and point cloud). The other settings regarding the single flight, the longitudinal and transverse overlapping were fixed to 80%. As concerning the speed, the maximum value was set to 5 m/s.

After fixing the flight characteristics necessary to obtain a good result in photogrammetric terms, we moved on to planning the different missions to cover the entire area. In this case, it was decided to set the maximum flight time for each mission within 30 minutes to work in complete safety and allow the sensors and system response after take-off to be verified each time. The flight was planned in VLOS mode, with co-pilot present and with assistance from the ground by personnel trained in mission characteristics and flight procedures. The survey area was subdivided into 16 missions, each covering a specific area of the city aiming to survey the entire city and considering the need to maintain VLOS throughout the flight and balancing the scheme considering the battery life and time (Fig. 1). Each area was first drawn in Google Earth and exported in .kmz format; then it was imported in DJI Pilot software where the previously defined flight parameters were set. The 16 flight missions were thus set to be used later during the autonomous flight of the Matrice 300.

Figure 1. Scheme of the 16 flight missions for the UAS survey of Sabbioneta. Some overlapping between adjacent areas was granted.

The flight project also required a well-conceived choice on methodologies for data georeferencing. We chose to use the NRTK link for the flight phase, and to proceed with the traditional method (indirect georeferencing) for the data processing phase. For this reason, coded markers were distributed and placed in several areas of the city during the flight operations, so that they could be recognized automatically in the pictures by the software.

2.4 Survey planning and regulation

When planning the drone survey of such a large urban inhabited area, it is essential to take safety and regulatory aspects into account. In Italy, the first regulation on UAS systems was issued by ENAC in 2013 and several new editions of that regulation followed. On January 1st 2021, the new Commission Implementing Regulation (EU) No. 947/2019 of 24 May 2019 on standards and procedures for the operation of aircraft, issued by EASA (European Union Aviation Safety Agency), came into force. This regulation aims to homogenize national regulations and ensure that the growing drone traffic throughout the European Union is safe and secure for people on the ground and in the air. For this reason, we choose to briefly mention, within this scientific article, the choices made not only in designing the flight from a photogrammetric point of view, but also with regard to flight safety. As already mentioned, following the regulations, all operations must be conducted in VLOS. And it is also necessary to guarantee certain requirements to work in LG-2020/001-NAV - Annex A.1-*Scenario Standard IT-STS-01*. Although the DJI Matrice 300 RTK has all the safety systems installed by the manufacturer, a parachute with a flight terminator was also installed on the system. The flight plan was shared with the local police force and the Municipality of Sabbioneta to warn the population of the planned overflight operations. In addition, for each of the 16 flight missions, a graphic sheet was drawn up (Fig. 2) showing the geographic area (area in which the operations are carried out), the contingency area (area that can be occupied by the drone while guaranteeing total control of the flight, which does not require flight termination) and the buffer area (area that, if invaded by the drone, requires flight termination). On that scheme were specified also the take-off point (and landing point if different), the position of the second pilot (to ensure visibility of the drone at all times), and the expected flyover time.

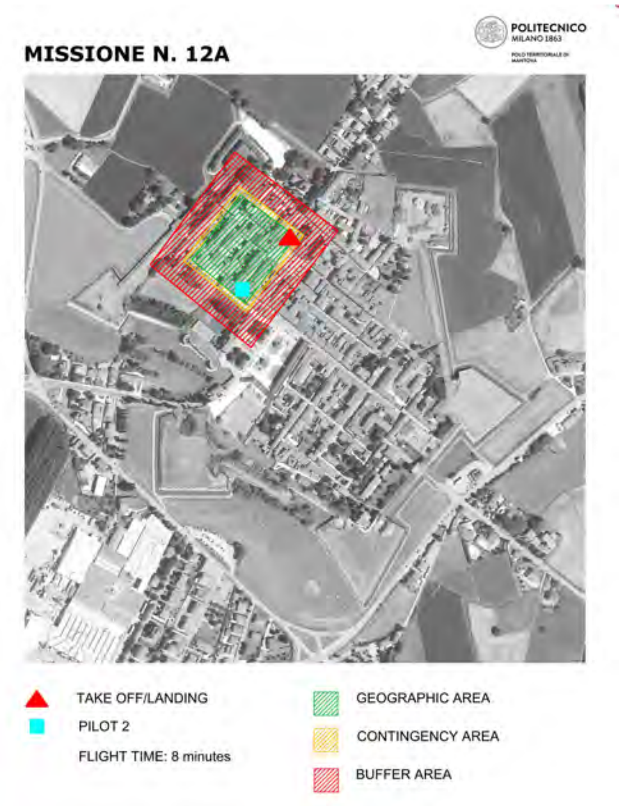

Figure 2. example of a single flight mission note document (in that case is the mission 12 specification sheet).

The police were also provided with a flight schedule with missions in temporal succession. During the design phase, consideration was also given to aspects related to the time of the flights. Thus, it was decided to operate in the central hours of the day in order to avoid too long shadows in the pictures. Inevitably, the design was also confronted with logistical and cost aspects: in fact, to lower the impact of logistics aspects and costs of the missions, it was necessary to keep the time frame short. In addition to the pilot and second pilot, other experienced operators, aware of flight operations, followed the drone’s path from the ground, urging people not to stand under the operating UAS.

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2.5 Data acquisition

The acquisition operations were conducted in two different periods (June 2022 and August 2022), as during the first acquisition the UAS system reported errors that inevitably delayed the acquisitions by a few months. This delay allowed further fine-tuning of the missions. The 16 flight missions were all carried out over three days, trying to concentrate operations in the middle hours of the day to avoid too long shadows (e.g., of buildings, trees, poles, and taller elements in general) that could affect the resulting orthophoto. Anyway, weather conditions, could not be changed and the survey took place on very sunny days. For this reason the presence of very sharp shadows in the photos could not be avoided on some areas of the city. During the three days of acquisition, the GNSS support necessary for the correct georeferencing of the photogrammetric model was also carried out. Leica GS18 T GNSS RTK receiver with Leica CS20 field controller was used with Network Real Time Kinematic (NRTK) Positioning, leaning on Leica Smartnet Italpos. We measured the coded target points, but also notable architectural elements on ground recognisable in the images (e.g., manholes corners).

A total of ca 10249 photos were taken in three working days. Considering the flight altitude and the camera resolution, the expected GSD was confirmed. All missions were set for nadiral picture acquisition, apart from missions 5 and 12 which were repeated for an oblique acquisition, to ensure buildings' façade reconstruction, because they involved the most relevant monuments of Sabbioneta.

3. PHOTOGRAMMETRIC PROCESS

Agisoft Metashape Professional (version 2.0.0) was used for the photogrammetric process on an AMD Ryzen 9 computer, with 16 cores, 128 GB RAM, and an NVIDIA GeForce RTX 3090 Ti graphics card.

Although the photographs acquired during the survey were taken in 16 different survey slots, they were all processed together in one single project. This choice was made to optimize the orientation of all images and for better error distribution. Since the UAS was connected to an RTK station, each picture was provided with the coordinates of the taken point, stored with WGS84 (EPSG:4326) reference system and ellipsoidal heights. The 10249 pictures were imported into the software together with their geographic coordinates (latitude, longitude, and altitude), attitude (yaw, pitch, roll), and their accuracy. The first attempt showed some problems in the direct orientation using the RTK data, probably because almost in each flight we notice loss of connection to the base station. For this reason, we decided to import images with their own coordinates and attitude but changing the accuracy to a higher constant value for all images, in order to have less influence on the orientation phase.

Then, the camera external and internal orientation parameters were computed and optimized; camera alignment was completed in 2.08 hours using "high" quality settings. 10240 photos were oriented out of a total of 10249; the 9 non-oriented photos were 9 photos taken consecutively and all were framing a completely green, homogeneous portion of the crop field.

As described in section 2.5, the coordinates of some notable points of the ground surface of the city and the center of photogrammetric markers carefully placed within the city before to conduct the survey, were measured by a GNSS receiver, and stored using projection WGS84 UTM 32N as reference system. These points were used as Ground Control Points (GCP) and check points along the process. GCP coordinates were imported and used to optimize and adjust the camera position, using the bundle adjustment (Verykokou and Ioannidis, 2018,Chiarini et al., 2014). 30 GCPs were used, well distributed around the city, and 9 check points were identified. Check points and GCP errors are reported by Table 2. The value of these errors in the XY plane are comparable with the accuracy of point acquired by NRTK and they are suitable to the 1:100 scale cartography, where the plotting error is 2 cm. GCP position and error estimations are reported by Figure 3.

	E (m)	N (m)	Elevation (m)
GCP	0.012	0.009	0.029
Check points	0.009	0.012	0.022

Table 2. RMS errors of GCP and Check Points after bundle adjustment.

Figure 3. Image of the sparse point cloud, composed by tie points, with locations of ground control points and check points. For each point its Z error is shown by the color and the XY error is shown by an ellipse magnified 1000 times.

According to the suggested workflow of the new release of Metashape (release 2.0.0) mesh model was computed directly from depth maps and not on the basis of the point cloud. Depth maps were computed in medium quality and using a moderate depth filter, in 3.8 hours. The mesh model was then generated exploiting them; it was computed in medium quality in 3.4 hours. The mesh model was composed of 152 million faces. Then, the orthomosaic (Fig. 4) was computed on the XY plane, with a pixel size of 1 cm, in 11.2 hours.

Agisoft Metashape version 2.0.0 allows the generation of the dense point cloud based on the mesh, by generating the points on the mesh surface, with a user defined spacing. By doing so the point cloud can be affected by some polygon simplification performed during mesh computation, so we have decided to compute it directly from the depth maps previously computed.

The dense point cloud was computed in medium quality from depth maps previously computed. The computation took 6.5

Figure 4. Resulting orthophoto of Sabbioneta, with a pixel size of 1 cm. On the right, there is a zoom on some areas of the city.

Figure 5. Perspective view of the dense point cloud, composed by 1.9 billion points.

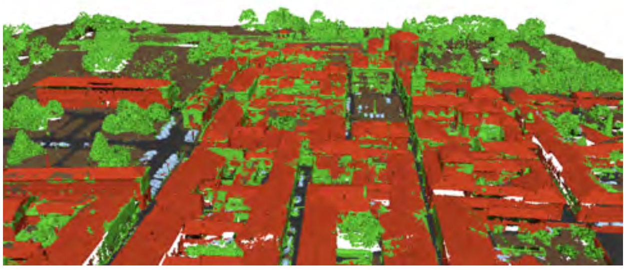

Figure 6. Segmented point cloud.

hours, the dense point cloud (Fig. 5) is composed of 1.9 billion points. The average point density was of 2500 points per square meter (computed in CloudCompare), corresponding to an average point spacing of 2 cm.

Then, the dense point cloud was exploited to perform an initial classification test. The automatic classification tool of Agisoft Metashape was used. This tool allows for the segmentation into ground points, or into several classes. The ground classification was performed in 2 hours. After a visual inspection, the results of the subdivision into ground and non-ground points was almost correct for the whole point cloud. Then, the automatic multiclass classification was performed. The confidence value was set to 1. The points were segmented into the following classes: ground, high vegetation, building, road surface, car. The segmentation was completed in 1.5 hours. After a visual inspection of the segmented point cloud, it was possible to note that many buildings’ facades were identified as ”high vegetation” class. Figure 6 shows the classified point cloud after multiclass classification.

4. DISCUSSION

Some considerations can be made basing on the presented test. The first observations concern the flight plan. Although we have tried to organize the flight missions taking care of every details, it is necessary to remember that still remain a number of possible issues that cannot be programmed (e.g., presence of visiting school groups, tourists walking around the city, public activities not planned/communicated to the police). It is therefore necessary to have the possibility, in agreement with the police, to modify in real time the flight missions to meet their needs.

Another observation, although already highlighted, concerns the design of the flight during the day. Obviously, the best flight conditions include the absence of wind and a cloudy sky to avoid the sharp shadows in the images. Programming the survey in the middle of the day should also help prevent long shadows on images. These conditions are not always easy to comply with, so it should be necessary to use photo editing software both in the pre-processing phase and in the post-processing phase. In the first step, the image quality could be partially improved by taking photos in raw mode, so that it could be possible to later modify them (e.g. using Adobe Lightroom) with a wider range of parameters to set. At the end of the photogrammetric process, however, it is possible to change the orthophoto to improve some issues otherwise difficult to control (e.g., shadows of lamp posts, presence of people, etc.).

Looking carefully at the camera positions after the alignment phase, it was noticed that not all the photos were taken with regular spacing. It was observed that in some missions the spacing between successive cameras, with consecutive numbering, was variable (Fig. 7), whereas this should be avoided to maintain proper overlap as planned. Since all missions were designed with dedicated software and executed automatically following the flight plan, the non-consistency in spacing between photos is unexpected. We believe that this is due to a momentary lack of communication or signal loss. This behaviour will be the subject of future investigation.

Figure 7. Example of irregular spacing between consecutive cameras.

The specific case of the urban historic center also brings considerations related not only to the aspects of flight and photogrammetric acquisitions, but also related to the use of markers for direct georeferencing. Indeed, the narrow streets of the historic center greatly lowered, and in many cases precluded, the GNSS survey of targets. As a result, markers in the narrower streets could not be surveyed and the accuracies were often lower than those measured in the open field. All this led to redefining the pixel size of the final image. Although the acquired images have a GSD of 5 mm, considering orientation and georeferencing errors, it was deemed appropriate to fix the final GSD at 1 cm, suitable for 1:100 scale representation.

The dense point cloud generated in the process was segmented. The purpose of this segmentation, carried out with the software's own tool, was to test if such an automatic process may also be reliable for a historic urban context, in which the shapes of buildings and the organization of elements are peculiar. With an initial visual analysis, the ground and non-ground classification appeared to be done correctly, while the multi-class classification showed areas with several misclassifications related, for example, to the "high vegetation" class (e.g., building facades identified as high vegetation) and the "road area" class not fully recognized. The performance of the classification will be the object of future studies, also testing different algorithms (not only the Metashape tool) in order to analyze its behaviour for the historic built environment. Previous researches carried out on the same case study and focused on the issue of mobility (Treccani et al., 2022) have highlighted some peculiarities of the historic built environment (e.g., coplanarity between street and sidewalks, use of various paving materials) that may generate classification errors on general classification tools.

5. CONCLUSIONS

In this paper we presented the UAS photogrammetric survey of a historic urban area: Sabbioneta. The UAS selected was the DJI Matrice 300 RTK. The photos taken on-site were exploited through a photogrammetric process to generate an orthophoto of the city with a pixel size of 1 cm. The computed dense point cloud was classified into ground and non-ground points and also into several classes by using the automatic tool provided by Agisoft Metashape.

The test performed allowed us to discuss the performance of the instrument in relation to the survey purpose and to the final result. It also allowed us to discuss the practical expedients implemented to cope with Italian and European UAS regulations. The presented approach is suitable for the generation of high-resolution orthophoto and highly detailed point cloud to be used for further urban studies. In addition, from the test developed, there is a need for further analysis inherent direct and indirect survey georeferencing. The purpose will be to verify the difference between the two strategies and evaluate the accuracy of the two methodologies.

The use of Agisoft Metashape tool for point cloud classification was just a first classification test. In future the point cloud will be manually classified to create the ground truth, and existing methodologies for point cloud segmentation through machine learning and deep learning will be tested. The segmented point cloud could be the basis for future modelling of 3D city models. Furthermore, the segmented point cloud could be used as a information container and test on the possibilities of data sharing on web platforms will be performed.

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