

ORIGINAL ARTICLE

Unmanned aerial vehicle data acquisition methodology and assessment of photogrammetric products for telecommunication mast inventory

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Abstract

UAV (unmanned aerial vehicle) data are widely utilized for the inspection of telecommunication masts, but the quality and accuracy of photogrammetric products largely depend on the method of data acquisition and flight parameters. This study proposes a methodology for flight trajectory planning and acquiring UAV imagery for inventorying telecommunications masts. A crucial component of the methodology is an application that facilitates flight mission planning and enables operators to collect reliable and repeatable data fast. An accuracy analysis was performed for both dense image matching (DIM) point clouds and 3D mesh models to evaluate quality of products with terrestrial laser scanning (TLS) point clouds used as the reference. A similar evaluation was performed with unmanned laser scanning (ULS) data. The experiments demonstrated that the mean distance between the DIM point cloud and the TLS data was not higher than 2 cm and standard deviation was 1.8 cm or less for all surveyed towers while for 3D mesh models these values were less than 1.2 cm and 2.6 cm respectively. A comparative analysis with ULS data also confirmed that both the DIM point cloud and the mesh model meet the accuracy criteria adopted in the research project.

Keywords: telecommunication mast, unmanned aerial vehicle, dense image matching, point cloud, 3D model

1 Introduction

Unmanned aerial vehicles (UAVs) are valuable tools for infrastructure inspection (Jalil et al., 2019; Jordan et al., 2018). In particular, photogrammetric products such as point clouds and mesh models can provide important information. Telecommunication masts, which were studied in the research project, are typically tall, slender and often open-lattice structures. The main contribution of this study is the development of a semi-automated image acquisition method for mast inventory, along with the demonstration that it can produce accurate and complete 3D models. A key motivation for this study is the lack of a universal image acquisition methodology suitable for different types of masts and their surrounding environments. Existing approaches often require case-specific planning or extensive manual adjustments, limiting their practical applicability. The proposed methodology addresses this

limitation by requiring only a short reconnaissance flight to characterize the structure, after which the complete image acquisition mission can be planned automatically. This improves the practicality and industrial value of UAV based mast inspections by reducing operator effort, shortening preparation time, and enabling consistent data acquisition across a wide range of mast configurations. Automatically inspecting and inventorying objects with such characteristics using photogrammetric methods is a challenging task due to issues with weak texture, hollow-carved structures, and self-occlusion (Huang et al., 2020). Standard nadir or grid-based flight missions are frequently insufficient for reliable reconstruction of slender vertical structures. Consequently, dedicated mission planning strategies, including orbital, helical, or multi-level flight trajectories, are essential to improve geometric completeness and image redundancy around tall objects. Mission planning software is often limited and lacks flight mission functions, such as orbiting

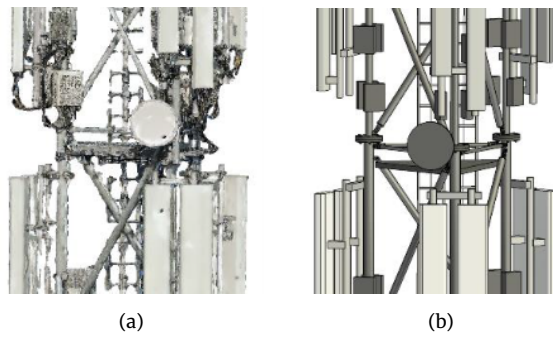


Figure 1: Comparison of DIM cloud and modelled tower structure in Revit: (a) DIM cloud, (b) solid model

around objects. Although helical and orbital flight paths have been investigated in previous studies, their application has focused, for instance, on flight control evaluation or environmental monitoring rather than on photogrammetric inventory of infrastructure objects. For example, helical trajectories have been used to assess autopilot performance and trajectory tracking accuracy (Looye, 2011). Such a data acquisition flight path was also applied in industrial monitoring tasks (Corbett and Smith, 2022). Although some studies have shown that UAV data acquisition for slender vertical structures can also be performed using vertical flights along individual faces of lattice towers (Wrzosek, 2023), the potential of orbital or helical flight trajectories for systematic photogrammetric data acquisition of telecommunication masts remains largely unexplored.

Well-planned UAV data acquisition is a prerequisite for generating reliable photogrammetric models that can serve as a basis for further analysis and digital representation of infrastructure objects. Therefore, one issue that posed a research challenge was the methodology for data acquisition in the form of mission parameters, as well as how to process UAV data to reconstruct the object and create a model with a high degree of geometric completeness, which provides the most reliable information about the objects. Consequently, the research presented in this study introduces a dedicated solution with particular emphasis on the selection and optimization of key flight parameters and image acquisition. By using a properly developed data acquisition methodology, it is therefore possible to obtain high-quality photogrammetric models. In subsequent stages of the project, models have been utilized for BIM management of telecommunication masts, leveraging Digital Twin technology.

In the process of creating a Digital Twin of objects from photogrammetric data, two approaches can be distinguished: a triangular mesh model or a solid model (Figure 1). While the generation of mesh models with texture from UAV images is an automated process, and such products provide a good representation that reflects the actual appearance of the object, it is essential to note that the Digital Twin also requires semantic information (Medeisis and Radis, 2022).

As mentioned, the use of photogrammetry to analyse telecommunication masts is not a new approach. Literature review indicates that the photogrammetric technique is a feasible solution for documenting and inspecting thin, tall objects, as demonstrated in the work of Widurski and Kurałowicz (2009). Moreover, the development of computer vision technology and improvements in the automatic generation of 3D models have made Structure from Motion (SfM) and Multi View Stereo (MVS) algorithms the most widely used methods in the process of reconstructing 3D models from images (Hofer et al., 2013; Knyaz et al., 2020). An application of point clouds from dense matching of UAV images using a telecommunication mast as an example object was presented in paper (Deidda et al., 2020). The results were used to develop a skeleton model of the tower, which can be further utilized in BIM or GIS

analysis.

Besides the photogrammetric products generated from UAV imagery, point clouds from Unmanned Laser Scanning (ULS) or Terrestrial Laser Scanning (TLS) data can also be used for 3D reconstruction of critical infrastructure facilities (Omairi et al., 2024; Qiao et al., 2024; Zhang et al., 2019). The research described in Szablowski's thesis (Szablowski, 2016) highlights the potential and limitations of using UAV imagery for 3D reconstruction using the example of the Tyhold tower in Trondheim, Norway. A comparison of dense image matching point clouds with laser scanning data showed that the combination of both methods provides more comprehensive documentation of such structures. Another interesting study was presented by authors Siwiec and Lenda (2022), who combined TLS and SfM to measure a 120-metre chimney. A similar approach to integrating two different technologies was demonstrated in the paper of Lenda and Marmol (2023). The study involved integrating ULS and TLS data for a water tower. The average point cloud mean merge error obtained was ~13 mm.

An important aspect in the context of developing 3D models for telecommunication masts is, of course, accuracy assessment. This raises the question of whether data obtained from UAVs provide sufficient geometric information to create an accurate 3D geometric model. To validate the accuracy of the geometrical 3D model, it is good practice to measure predefined reference points using traditional geodetic methods or to utilise reference models based on design documentation (Wrzosek, 2023). However, it is possible that the documentation is incomplete or outdated, making it challenging to create a solid BIM model that can then serve as a reference. In such cases, for example, TLS data can be used as reference data sets for evaluating photogrammetric products obtained from UAV image processing (Remondino et al., 2014; Zachar et al., 2022), as TLS provides direct distance measurements with high accuracy and high point density. A comparison of 3D data from two different sources can be performed using an analysis of the distance between point clouds or between a point cloud and a mesh model (Sui et al., 2025). This enables an assessment of geometric quality, accuracy, and completeness. In the following study, two types of reference data were used to evaluate point clouds from dense image matching and mesh models: TLS and ULS. Although data from TLS provide high accuracy, field measurement is time-consuming. ULS, on the other hand, allows for faster data acquisition and mapping of the object from above, which is particularly important for very tall structures where the upper parts are difficult to access from ground level.

Some limitations of the proposed methodology can be indicated, particularly resulting from varying environmental conditions, different tower geometries, and GNSS-denied or GNSS-challenging environments. The proposed methodology, which was developed for a multi-temporal image acquisition for each mast, does not provide for using Ground Control Points. To ensure the proper georeference, it is required that images contain RTK metadata. A few examples have pointed to certain limitations in this regard for lower-level images when there is tall vegetation near the base of the mast. One of the unique challenges for image acquisition around telecommunication masts is the antennas negative impact on UAV spatial orientation.

Active sensors, such as terrestrial or UAV-mounted laser scanners, can provide highly reliable geometric information, particularly in areas with limited visual texture. However, terrestrial laser scanning is limited by the scanner's range and the accessibility of the surrounding ground area. Furthermore, both terrestrial and airborne LiDAR systems are typically more expensive and often involve more complex mission planning, sensor calibration, and data processing steps, such as strip alignment, which in case of horizontal strips (orbits) would require a human-in-the-loop approach. In contrast, image-based photogrammetry simultaneously provides high-resolution imagery and a 3D model. This is particularly advantageous for mast inspection, where specialists require not only an

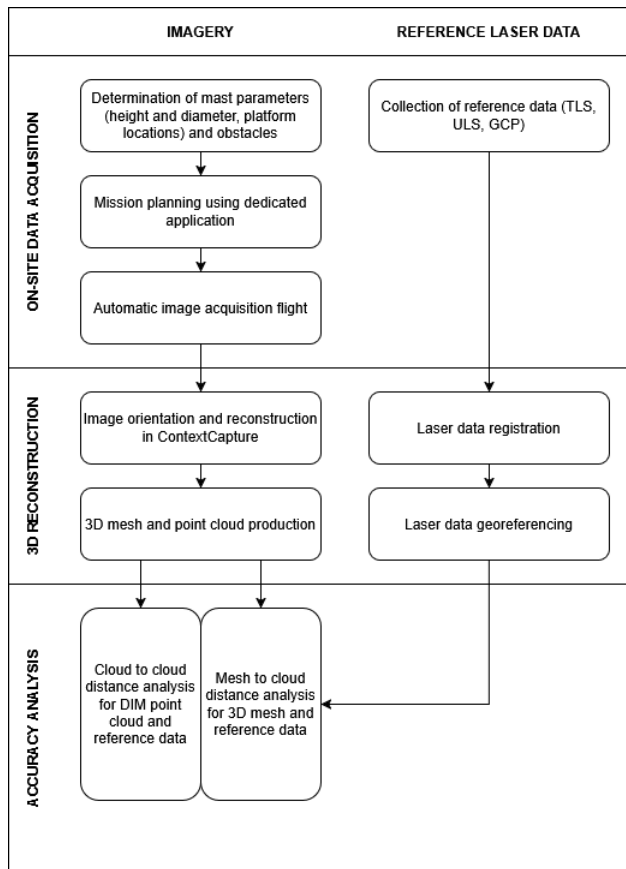


Figure 2: Data acquisition, processing and analysis flowchart

accurate geometric representation but also georeferenced images that enable detailed visual assessment of structural elements, antennas, cables, and other mounted equipment. Furthermore, image acquisition and photogrammetric processing workflows are well suited to automation, making them a feasible solution for routine inspections of various mast types.

Regarding the reconstruction itself, despite the low beam divergence, short scanning distance, and high measurement resolution achievable with laser scanning, the resulting point clouds may not provide a sufficient number or an appropriate distribution of points on individual mast elements to enable reliable reconstruction of their geometry. In contrast, dense image matching can produce a more complete representation of the structure when adequate image coverage and overlap are ensured. The proposed methodology employs the principle of georeferencing using aerotriangulation based on RTK image positions due to its practical applicability and the widespread availability of high-accuracy GNSS observations for image orientation.

Despite the advantages of UAVs in infrastructure inventory, there is a noticeable lack of standardised recommendations regarding the methodology for designing flight missions and data acquisition, as well as criteria for assessing the quality of 3D products. There is therefore a clear need for research focusing on strategies and approaches for data acquisition, processing and evaluation for this type of application.

2 Methodology

The research process was divided into three main stages: field data acquisition using UAVs, 3D reconstruction of objects, and accuracy analysis using reference data, as shown in the block diagram in Figure 2.

2.1 Dedicated solution for data gathering and flight trajectory optimization

One of the research elements was to acquire data in a reliable form and of sufficient quality to be processed further in more advanced analysis (Alsadik and Nex, 2021; He et al., 2019; Isa et al., 2019; Sathia Raj et al., 2020). Since the UAV proved its usability in the process of inventory, the next step was to optimize the procedure so that it is more effective. Traditional UAV flight planning tools — such as Pix4D, UgCS, or Litchi — offer general-purpose mission design features but are not well-suited for the specific conditions surrounding telecommunication masts (PIX4D, 2021; SPH Engineering, 2023; VC Technology Ltd, 2023). These objects often include metal frameworks, supporting cables, antennas, and other elements that create interference zones and physical obstacles. The default settings of standard mission planners are usually insufficient, failing to consider the aforementioned elements that directly impact the mission's time and data quality. On the market, there are tools with an application dedicated to vertical construction flights. The default paths offered within those tools are limited. They do not consider the surrounding of the mast and do not consider the individual specification of the mast configuration, i.e., number of platforms or types of antennas, etc. From the workshop and feedback from the GSM companies that were provided, the platforms with antennas are the most crucial and important element of the whole construction. Thus, the individual approach and UAV sensor settings are key factors for effective data gathering. The main advantage of the developed tool provides a trajectory that considers all individual aspects and features of the selected mast. That approach ensures the path fits the construction, maintaining proper data quality. Not only is the dataset more accurate (confirmed by the research), where repeatability is a key factor, but the time of the path generating and executing the flight is also better. The primary rationale behind the tool was to support the process by bridging the gap between research-driven photogrammetry and real-world industrial inspection. Existing commercial systems enable basic mission planning, but they lack the flexibility and intelligence necessary for navigating complex vertical objects. They typically generate simple circular flight paths that overlook crucial parameters, such as antenna placement, supporting cables, or environmental obstacles. Consequently, the resulting point clouds are often incomplete or inaccurate, making them unsuitable for high-precision applications such as structural analysis or creation of digital twins. The new application developed within this research directly addresses these deficiencies by allowing adaptive trajectory generation based on real object geometry and surroundings. A fundamental source of variation among vertical structures concerns their height, the number and configuration of mounted components, and, most critically, the characteristics of their immediate surroundings, which often constrain feasible flight paths. The presence of antennas introduces additional operational challenges, further complicating the safe execution of UAV missions around such installations. An equally important safety consideration involves the use of guy wires for mast stabilization. These are typically steel cables secured between the structure and the ground using specialized anchors, effectively reducing the structure's accessible perimeter. To ensure the safety of flight operations, the UAV must consistently maintain a minimum separation distance from any potential obstacle. Consequently, before formulating the methodological framework, it was necessary to establish precise guidelines governing both the required quality of the collected data and the key parameters defining the optimal flight trajectory.

The methodology for conducting optimal UAV inspection flights focused on two primary aspects. The first and most critical objective of the optimization process was to reduce the overall duration of the operation. Equally important, however, was the need to maintain specific quality parameters for the data collected by onboard sensors. To minimize both mission preparation time and in-flight

duration, it was necessary to define constant configuration parameters for the sensors, particularly camera settings and distance from the vertical structure's axis (e.g., chimney or mast). These tasks required a series of field experiments, including multiple image acquisition flights under controlled conditions. Consequently, numerous flights were performed under consistent weather conditions, systematically varying key flight characteristics, including UAV speed, distance from the structure's axis, camera settings, and pitch angles. The dataset was done based on the matrix of various configurations of the drone-mast position, including different flight altitudes and various angles. Those iterations allowed to find the optimal parameters. Over forty experimental flights were conducted with different UAV configurations to acquire datasets used for generating point clouds and mesh models of the structure. The collected data were subsequently analysed by a research team specializing in image processing to produce a digital twin of the mast.

This process followed an iterative approach, allowing for the continuous refinement of initial flight parameters to enhance operational efficiency. Based on the experimental results, optimal flight parameters were determined. The most significant variables included UAV speed, camera orientation (pitch angle), and distance from the structure's axis. The study demonstrated that the UAV's speed should not be lower than 1.0 m/s or exceed 1.5 m/s. Lower speeds resulted in image instability and, in some cases — particularly near antennas — caused electromagnetic interference, leading to communication loss and reduced positional accuracy. To mitigate these risks, the lower threshold of 1.0 m/s was adopted. The optimal distance from the structure's surface was established at approximately ± 6 meters, while the camera tilt angles were fixed at ± 30 degrees. These settings provided data acquisition from suitable perspectives while preserving the highest achievable accuracy. Various flight patterns were also tested during the trials to evaluate their efficiency and suitability for photogrammetric reconstruction.

The application dedicated to the UAV operator allowed for the indication of all crucial elements and surroundings of the mast, so the trajectory was fitted to maintain sufficient parameters, and the data were reliable for further analysis. In Figure 3, there is a panel in the app where the operator enters the required heights and distances to generate the flight plan. Before the UAV operator performs the flight, an initial preflight is needed. This operation is always a must-have before every inspection optimization process. However, during the development of the cyclic inspection, some parts of the process can be completed much faster because the application allows rerunning the previously used trajectory. This feature is one of the most important and valuable ones for GSM companies, as it enables one-to-one replication of the flight trajectory, allowing historical data to be viewed with great detail. The photos are taken from the exact position; thus, the history of the elements is easily visible. During preflight, the operator must note and enter the key values of the environment and the mast in the application form. Having all necessary data, the operator chooses the type of inspection (orbits, optionally spiral or vertical for challenging guyed masts scenarios). The default settings for vertical construction itself are entered in the application, i.e., velocity, distance, and number of pictures. Those are the results of the research, and those values are the effect of the optimization process. If the operator needs to change the values, it can also be done. Consequently, the tower platforms (number and type) are implemented into the app, and the full trajectory — orbits + platforms — is generated and exported as a KML file that is easily accepted by the DJI M3M UAV.

The presented solution constitutes an original concept that has been developed and validated through extensive testing by UAV operators. The proposed measurement methodology has significantly enhanced the efficiency of UAV utilization for inspection flights while maintaining a high standard of data quality. The current implementation primarily focuses on vertical structures, such as masts, antennas, and chimneys. The primary advantage of implementing the application for the process is maintaining data quality

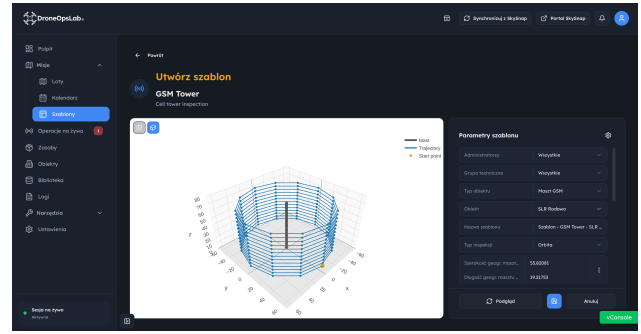


Figure 3: Application panel with key parameters of the mast and surroundings

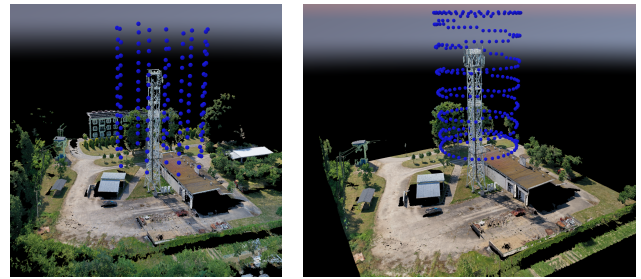


Figure 4: Various approaches for mast inspection trajectories

and reducing operational time. Another benefit is that for a periodic process, the trajectory is already fitted, allowing the data to be easily compared to determine the ageing process or identify construction defects. In Figure 4, an example of a generated trajectory is presented. Left — spirals method, and right — orbits.

2.2 Data acquisition

A common characteristic of most telecommunication masts is their slenderness, which necessitates a different approach to planning the acquisition of UAV imagery compared to terrain mapping. Due to the varying characteristics of tower construction, it was necessary to plan flight missions with universal parameters that allow for reconstruction with a high degree of completeness and detail, regardless of the type of facility.

At the stage of determining the optimal photogrammetric processing methodology for lattice structures, the high dependence of reconstruction quality on the geometric configuration of the image block was repeatedly confirmed. The way the data were acquired was a key factor in creating a complete mesh model of the tower. A regular parallel strip mission (in this case, vertical strips), which is intuitive from the perspective of aerial photogrammetry, proved to be an ineffective approach for thin and tall structures. Such a geometry of an image block is only applicable for missions around guyed towers, due to much better control over the UAV's position and predictable trajectory from the operator's perspective on the ground. However, it has limited effectiveness in reconstructing lattice structures.

In a series of preliminary experimental flight missions, the proven solution was to perform a series of circular so-called "orbits" centred on the longitudinal axis of the tower. Assuming appropriate intervals (or bases) between consecutive images, this method of data acquisition yielded the most complete results. Additionally, this configuration enables consideration of the object's diagonal changes. Due to the large number of devices and surface elements present in tower platforms, a modified image acquisition is necessary for these parts of the construction. Ultimately, the proposed solution for the telecommunications tower involves implementing



Figure 5: Geometric artifacts in areas occluded by objects on the maintenance platform and fixed camera pitch angle (orange boxes). Orange arrows — approximate elevation and camera pitch of “orbits”

a basic methodology for the structure (beams and angle bars) and a separate acquisition strategy for the platform. To determine a universal data acquisition methodology, the following parameters were considered:

- distance between the camera and the tower,
- camera pitch angle,
- horizontal distance between consecutive images on one “orbit” (analogous to the base between two successive images),
- vertical distance between consecutive “orbits” (analogous to the base between images from adjacent strips).

The areas requiring a special approach are maintenance platforms, which are parts of the tower that are characterized by the presence of horizontal surface elements such as grill flooring that allow personnel to move within the platform and equipment with a significant cross-section (such as antenna dishes). When acquiring images for platforms, it is necessary to vary the camera’s tilt to mitigate the areas of blind spots caused by those objects. An experiment was conducted in which multivariate flight missions were performed around a part of the tower containing two maintenance platforms.

Acquired data were processed in ContextCapture software. During the 3D reconstruction process, areas with insufficient visibility were marked by geometric artifacts. For those parts, no texture could be assigned to facets of the mesh, and they were considered incorrect. To assess the completeness and correctness of reconstruction, the ratio of incorrect points to total points of dense point cloud sampled from the 3D model was calculated. To assess the pitch angle influence on the quality of reconstruction, eleven variants were performed (A–E and A’–F’, Table 1). Photos were acquired using DJI Mavic 3 Enterprise UAV. The flight distance was constrained by the closest safe separation from the antennas and was set to 10 m from the mast’s vertical axis and approximately 7 m from the nearest structural elements. At these distances, the GSD ranged from 0.9 mm for the closest features to 1.8 mm for the most distant ones.

The results of the analysis indicate that more than three percent of all points are invalid in variants with any constant camera pitch angle (Figure 5). Fixed pitch angle value results in insufficient imaging of parts of the object in occluded areas, which consequently impairs the quality of the model. Artifacts (non-textured vertices) are present in insufficiently imaged areas. As expected, the greater

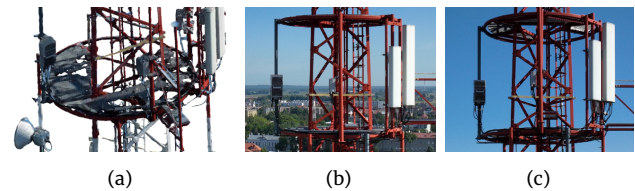


Figure 6: Missing elements of horizontal surface objects in mesh mode. Data were acquired with a camera pitch of 0°: (a) mesh, (b) and (c) photos from adjacent orbits

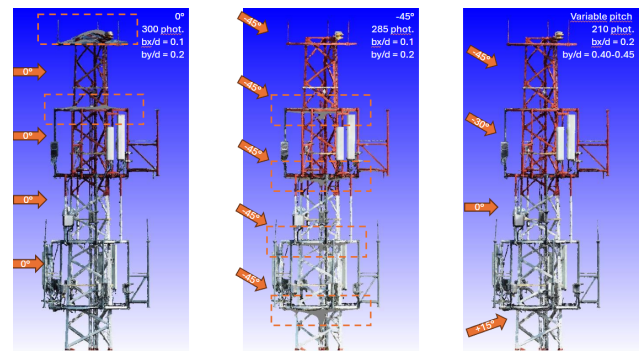


Figure 7: Influence of camera pitch angle on mesh model completeness. Left — fixed 0° pitch angle, middle — fixed -45° pitch angle, right — variable pitch angle. Orange arrows serve as an illustrative element of approximate elevation and camera pitch of “orbits”

the pitch angle, the greater the magnitude of this issue. Among the variants with a constant camera pitch angle, the smallest share of invalid points was achieved for the 0° variant. At the same time, for the 0° variant, the incompleteness of the horizontal surfaces of the model reconstructed using data acquired with the camera facing perpendicularly to the object should be noted (Figure 6). This is primarily due to the unfavourable angle from which these surfaces are photographed, and they are additionally obscured by devices in the outer part of the platform. Later, variable camera pitch angle variants were carried out by sub-selecting orbits from previous fixed-pitch variants (Figure 7). In these variants, problems with image orientation were observed in the case of varying strip (orbit) bases (i.e., distances between orbits, variant E). Subsequent variant F’ assumed similar distances between orbits (base to distance ratio 0.4–0.45) as well as optimization of flight time by reduction of images per orbit (base to distance ratio 0.2 within orbit). Despite the reduced number of images, variant F’ has the best quality in the visual assessment, the least number of artifacts (Table 1), and almost four times shorter processing time in ContextCapture software (F’: 11 min, E: 43 min). The computational requirements of the proposed workflow are moderate and compatible with commercially available high-performance workstations. All processing was performed on workstations equipped with 128 GB of RAM and an NVIDIA GeForce RTX 3080 Ti GPU. The processing software utilizes GPU acceleration for computationally demanding tasks while employing multi-core CPU processing for CPU-intensive algorithms.

This hardware configuration enables efficient processing of the largest datasets evaluated in this study, comprising more than 2,000 images acquired with the DJI Mavic 3 Enterprise. During testing, the *Ultra* reconstruction quality setting provided marginal improvements in the quality of the reconstructed 3D model while requiring substantially greater processing time and memory. Therefore, standard *Extra* reconstruction settings offer more efficiency for routine use. From the perspective of large-scale deployment, the workflow is readily scalable through parallel processing. As image datasets are processed independently, the practical scaling

Table 1: Camera pitch angle variants

Variant	Pitch angle	Number of photos	Base/distance ratio (within orbit)	Base/distance ratio (between orbits)	Total number of points [M]	Incorrect points [M]	Ratio of incorrect points
A	0°	300	0.1	0.2	17.16	0.72	4.2%
B	-30°	335	0.1	0.2	22.70	2.08	9.2%
C	-45°	285	0.1	0.2	26.60	3.38	12.7%
D	+15°	365	0.1	0.2	20.09	1.05	5.2%
E	variable (-45°, -45°, -30°, -30°, 0°, +15°, +15°)	412	0.1	0.2	20.06	0.73	3.6%
A'	0°	152	0.2	0.2	16.34	0.59	3.6%
B'	-30°	169	0.2	0.2	21.24	2.04	9.6%
C'	-45°	146	0.2	0.2	24.35	3.41	14.0%
D'	+15°	189	0.2	0.2	18.63	0.76	4.1%
E'	variable (-45°, -45°, -30°, -30°, 0°, +15°, +15°)	210	0.2	0.2	20.09	0.23	1.2%
F'	variable (-45°, -30°, 0°, +15°)	134	0.2	0.40–0.45	20.39	0.04	0.2%

strategy is to allocate one processing engine (workstation) per image dataset. This approach enables horizontal scaling of processing capacity without modifications to the proposed methodology.

The proposed image acquisition methodology for the platform involves varying the camera pitch angle per orbit. Thus, to completely photograph the platform and its elements, it is necessary to change the angle, which must be done gradually so that the content of images from adjacent orbits is both sufficiently similar to allow orientation of those images and, at the same time, cover the areas occluded from other orbits. Additional orbits with variable angles were proposed, consecutively: -30°, -15°, 0°, and +15° to optimize flight time near the antennas while maximizing data acquisition completeness. In the experiment, larger occlusions were observed for a mission with a constant pitch of -45° compared to -30°, which is an expected consequence of the high camera pitch (better visibility of objects above the obstacles, but worse below them). The optimization of data acquisition time led to the omission of orbits with a -45° pitch. The -30° pitch angle was adopted as the maximum pitch angle for this methodology, and a -15° pitch angle was added to ensure a proper contextual link between -30° and 0° orbits. Variable pitch angle variants were also conducted in the experiment, which demonstrated that changing the angle by 15° between adjacent orbits enables correct image orientation for each tested object. Thus, it was assumed that orbits of extreme pitch angles (-30° and +15°) will be performed for the platform, allowing for the minimization of areas occluded by larger objects, as well as intermediate orbits (-15° and 0°), the number of which depends on the height span of the platform. Those photos are intended to increase the number of observations (from an image orientation standpoint).

Due to the spatial characteristics of the lattice objects and the geometry of flight strips ("orbits"), the determination of frontal and side overlap of the images was abandoned in favour of determining the intervals between consecutive images/"orbits" based on base-to-distance ratios. Initial experiments revealed difficulties in reconstructing lattice tower objects based on sets of images with base-to-distance ratios exceeding 0.5, both within a single "orbit" (B_x/D) and between consecutive "orbits" (B_y/D). In an experiment conducted on another tower, the effect of base ratios (B_x/D) and (B_y/D) on model completeness was investigated with a terrestrial laser scanning (TLS) point cloud as a reference (Table 2). Both variants with increased base ratios (lower overlap) exhibited worse

Table 2: Mean distance and standard deviation in cloud-to-cloud analysis in relation to TLS reference data

Variant		Mean distance	Distance st.	Number
B_x/D	B_y/D	[cm]	dev. [cm]	of photos
0.2	0.1	3.3	2.3	208
0.1	0.2	2.9	2.5	295
0.1	0.1	1.5	2.0	415

completeness, as measured by the mean distance to the reference TLS point cloud and its standard deviation, compared to the base approach of $B_x/D = B_y/D = 0.1$ (Figure 8). Since the base approach did not provide significantly more complete reconstruction but is, in fact, cumbersome in terms of dataset size, it was decided that using $B_x/D = 0.2$ would decrease the dataset size by half, simultaneously optimizing the data acquisition and processing process with minimal quality loss to the reconstruction. Earlier experiments have proven that $B_y/D = 0.4$ allows for reasonably complete reconstruction, providing variability in pitch angle between orbits.

The proposed solution for the image acquisition strategy for telecommunications towers is to implement a base methodology for the main structure of the tower and an independent method for the tower maintenance platforms:

1. Methodology for image acquisition for the telecommunications tower consists of the following guidelines:
 - (a) images acquired from the nearest safe distance (considering the area of influence of Fresnel zones around the tower devices),
 - (b) flight mission geometry in the form of concentric orbits at different altitudes with centres on the vertical axis of the mast,
 - (c) the horizontal distance between consecutive images on one orbit is based on a base-to-distance ratio (B_x/D) of 0.2,
 - (d) the vertical distance between consecutive orbits is based on a base-to-distance ratio B_y/D equal to 0.4.
2. Furthermore, for the main structure of the tower:
 - (a) camera pitch angle during image acquisition is equal to -30°.

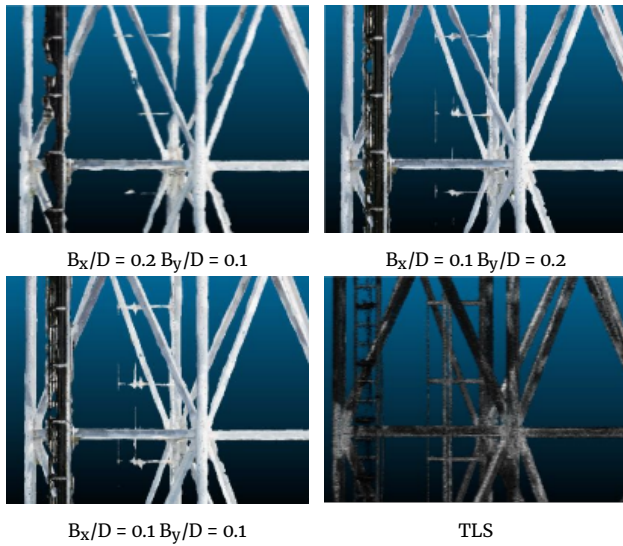


Figure 8: Comparison of TLS and DIM point cloud data for three variants of flight mission base ratios configurations

3. Whereas for the platform:

- (a) camera pitch angle for extreme orbits of -30° (highest), $+15^\circ$ (lowest), imaging the upper and lower limits of the platform, respectively. Their altitude should be adjusted to account for the pitch of the camera (vertical shift: $\Delta h = D \tan \alpha$, where α is the angle of pitch of the camera). The first intermediate orbit is located below the top one, with a pitch angle of -15° . The remaining intermediate orbits' pitch is equal to 0° .

In points 1c and 1d, the base ratio is the ratio of the base between two photos to the distance from the imaged object. There are separate base ratios for consecutive images on one orbit (base is a horizontal distance) and pictures on consecutive orbits (base is a vertical distance).

ContextCapture was chosen for photogrammetric processing due to its availability of settings and presets for the image alignment process, specifically designed for slender objects, such as “Orbit around thin vertical structure”. The initial processing already showed that ContextCapture can reconstruct lattice objects with high completeness. The processing allowed to identify problematic objects in terms of 3D reconstruction, which include:

- loose bundles of cables that do not form a single cohesive bundle,
- devices of small cross-section (cables, antennas, smaller beams),
- elements located inside the structure (ladder rungs, beams, and rails).

This methodology was designed not only to deliver high quality and completeness of mesh models, but also to ensure their universality regardless of the type of tower and to optimize the use of time and resources (flight time, number of photos, and computing power required for processing).

2.3 Reference TLS data acquisition

Terrestrial scanning data were acquired with the Leica RTC360 Scanner and registered using the Cloud-to-Cloud (C2C) method in the Cyclone REGISTER 360 software. The data were georeferenced in the PL-2000 system using Ground Control Points surveyed with the GNSS RTK method using Leica GS07 receiver. Basic information for each object is summarized in Table 3. Figure 9 shows example TLS point clouds, displayed by intensity.

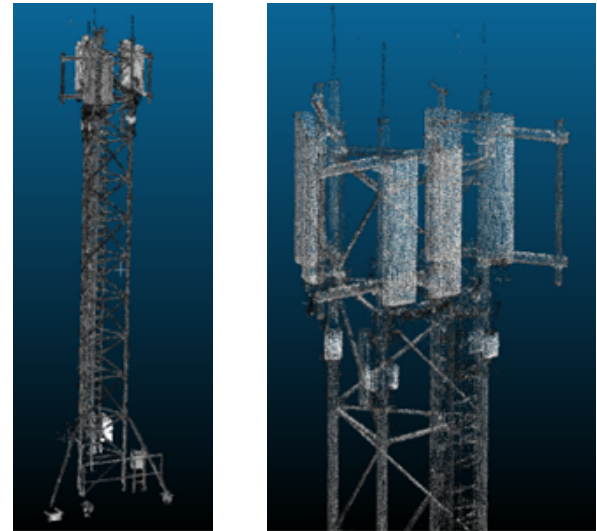


Figure 9: Example reference TLS point clouds for objects obtained during the project

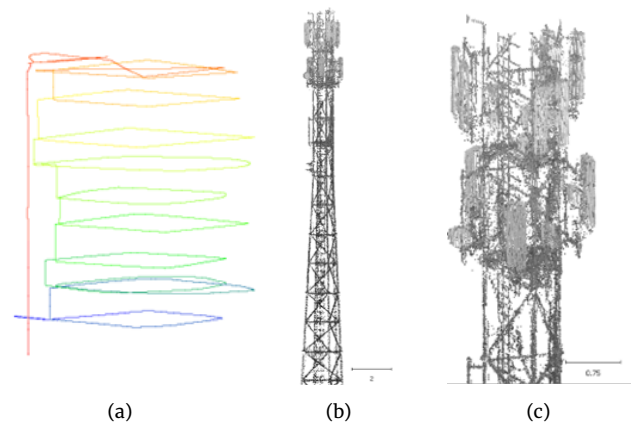


Figure 10: (a) UAV laser scanner trajectory, (b) ULS data of lattice telecommunication tower, (c) ULS data of tower devices and maintenance platform

2.4 Riegl miniVUX-3 UAV laser scanning data acquisition

Another source of reference was data collected with the Riegl miniVUX-3 UAV laser scanner (ULS) mounted on the DJI Matrice 300 RTK platform. The data were obtained as a reference source to assess the accuracy of telecommunications tower models reconstructed from imagery, as shown below (Figure 10). The flight was conducted in a nine-orbit scenario in manual mode. The resulting point cloud exhibited high spatial consistency.

3 Results

The analysis aimed to examine the accuracy of the DIM point clouds using TLS data as a reference. The research project assumed that for a model to be considered sufficiently accurate, the mean error (calculated relative to the TLS point cloud) should be less than 2 cm for DIM point clouds and less than 5 cm for a 3D mesh model produced with the same imagery. These accuracy thresholds were based on practical requirements of mast inspection and equipment inventory. The TLS dataset was assumed to provide complete coverage of the mast and was therefore used as a reference for evaluating the completeness and geometric accuracy of the image-based reconstruction. Under this assumption, significant values of the

Table 3: Summary of information on TLS data obtained for objects surveyed during the project

Tower ID	Structure type and height	Number of setups	GCPs	C2C alignment accuracy [cm]	Absolute mean error between the TLS point cloud and the reference GCPs [cm]
1	Steel lattice tower, 91.25 m	27	7	1.0	<10.0
2	Chimney, 58 m	19	4	0.7	<10.0
3	Steel lattice tower, 40 m	19	4	0.6	<10.0
4	Steel lattice tower, 43 m	23	6	0.4	1.6
5	Steel lattice tower, 45 m	27	7	0.7	0.3
6	Steel lattice tower, 11.5 m	14	4	0.5	0.5
7	Steel lattice tower, 50 m	18	6	0.6	0.6

cloud-to-cloud distance indicate areas where structural elements may be missing or inaccurately reconstructed in the image-based 3D model.

3.1 DIM point cloud results

The results of the DIM point cloud accuracy analysis in relation to reference data TLS are presented below. The differences between the clouds were calculated using CloudCompare software. Table 4 presents a summary of the results of the DIM point cloud accuracy analysis. The experiments showed that the accuracy criteria for the point clouds were met. Figure 11 illustrates the differences in distance between the point cloud generated from DIM and the point cloud obtained from TLS, as well as a histogram of C2C (cloud-to-cloud) signed distances for two example masts of varying heights (17 m and 45 m).

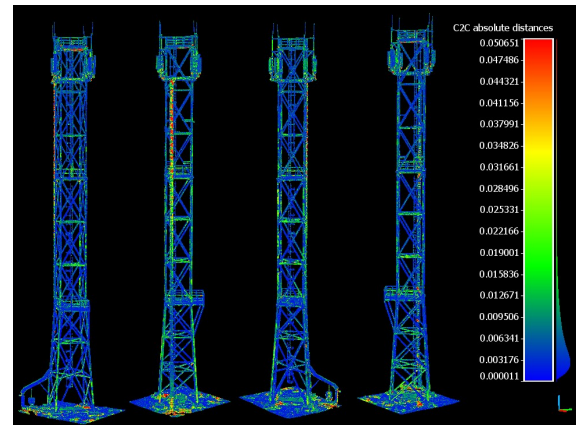
Table 4: Accuracy analysis of DIM point clouds against TLS reference data

Tower ID	Average C2C distance [cm]	Standard deviation [cm]
1	2.0	1.6
2	1.9	1.8
3	1.5	1.2
4	1.0	0.9
5	0.8	0.8
6	1.0	1.5
7	1.5	1.5

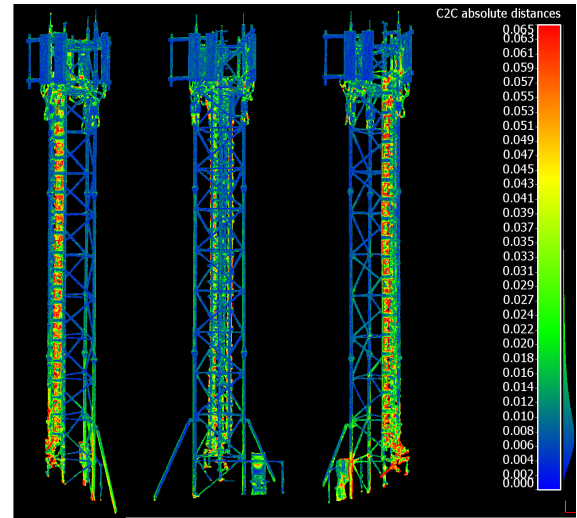
3.2 3D mesh model results

Similar analyses were made for mesh models obtained from DIM. The results of the accuracy analysis are presented below (Table 5). The distance between the mesh model and the TLS point cloud for two example objects is presented in Figure 12, along with the corresponding distribution of C2M (cloud-to-mesh) signed distances illustrating the magnitude and spread of deviations.

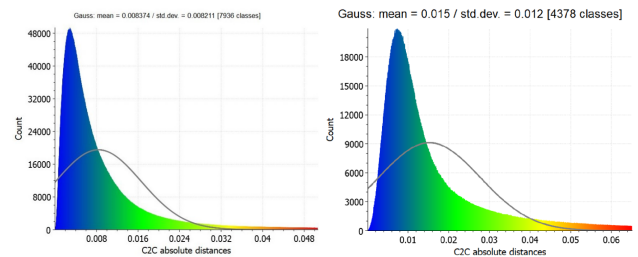
Experiments conducted as part of the project demonstrated that the accuracy criteria for 3D mesh models of the telecommunications tower, obtained from UAV images, were met. The methodology for data acquisition and processing developed within the project enables the generation of products that meet the accuracy requirements and can serve as a source of spatial and semantic data for constructing a Digital Twin of a telecommunications tower.



(a)



(b)



(c)

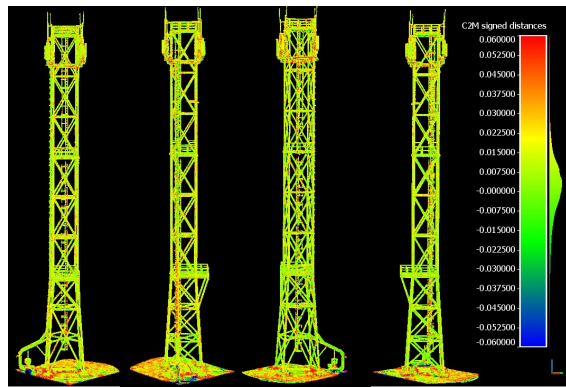


(d)

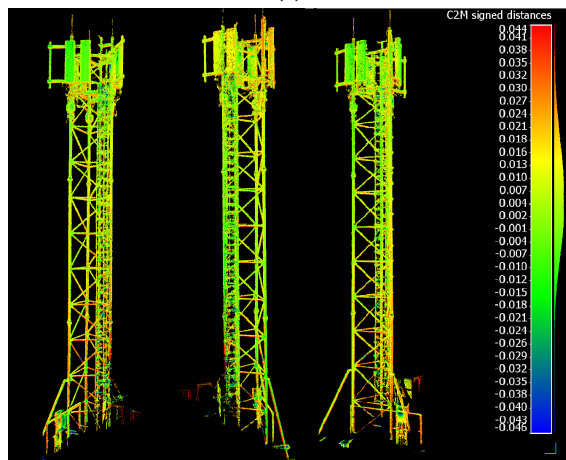
Figure 11: Distance between the DIM point cloud and the TLS point cloud for: (a), (c) 45 m and (b), (d) 17 m objects — side view and histograms

Table 5: Accuracy analysis of DIM point clouds against TLS reference data

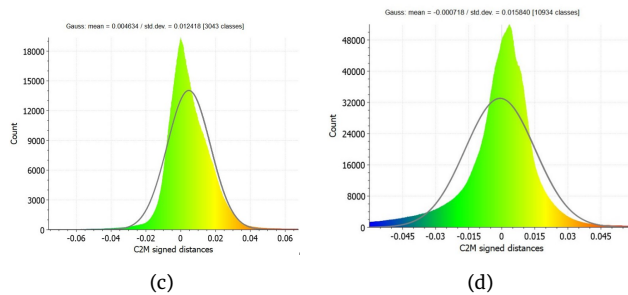
Tower ID	Average C2C distance [cm]	Standard deviation [cm]
1	1.2	1.9
2	0.1	2.6
3	0.6	1.4
4	0.5	1.2
5	0.1	1.6
6	0.2	1.3
7	0.4	1.9



(a)



(b)



(c)

(d)

Figure 12: Distance between the mesh model and the TLS point cloud for: (a), (c) 45 m and (b), (d) 17 m objects — side view and histograms**Table 6:** Accuracy analysis of DIM point clouds against TLS reference data

Product	Average C2C [cm]	Standard deviation [cm]
DIM cloud	2.0	1.4
Mesh model	0.2	3.0

3.3 ULS point cloud results

As mentioned in the introduction, ULS can be a valuable solution for objects and areas that are difficult to access or where methods such as TLS are not feasible. In some cases, the height of the object may exceed the range of a ground-based scanner, making scanning with a UAV an alternative. In addition to TLS data, ULS data were also used as reference data for evaluating products from UAV images. The ULS point cloud for one of the telecommunications towers was used to assess the accuracy of UAV data photogrammetric processing products, following a similar approach to that taken for TLS data.

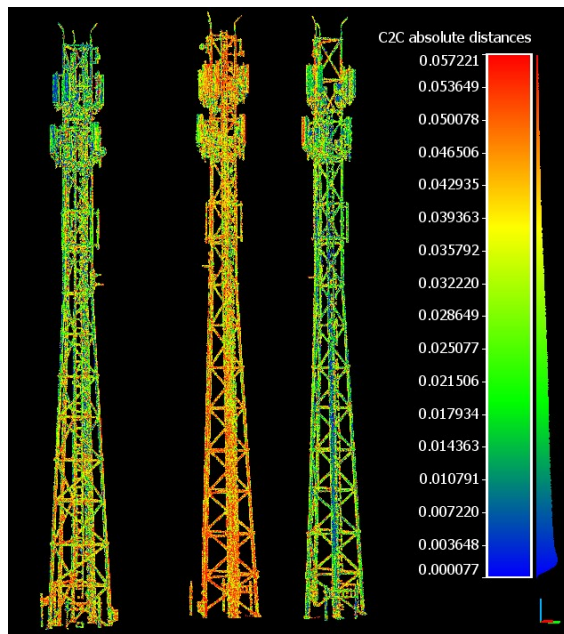
The results presented in Table 6 show that the average distance between the DIM cloud and the ULS cloud was 2 cm, with a standard deviation of 1.4 cm. For the mesh model of the examined telecommunications tower, the average distance between the model and the ULS point cloud was 0.2 cm, with a standard deviation of 3 cm. This means that the results meet the accuracy requirements set out in the project, with a discrepancy of less than 2 cm for the DIM point cloud and less than 5 cm for the mesh model. Figure 13 presents the results of distance differences between products (point cloud from DIM and mesh model) and reference data from ULS.

4 Summary

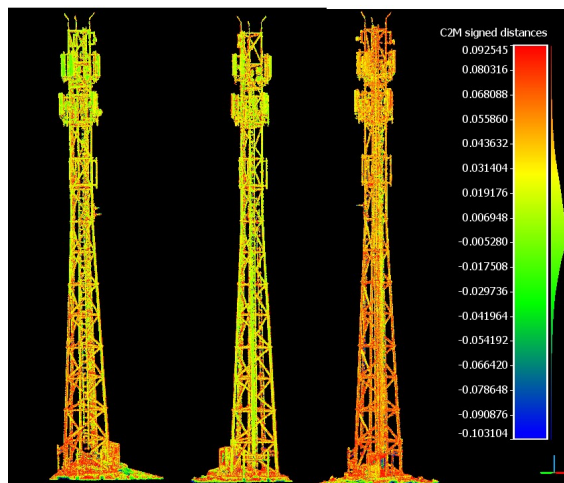
Photogrammetric UAV data, when acquired and processed using the proper methodology, provide products with high accuracy and completeness. Due to the spatial precision and high resolution of photogrammetric data, it is possible to reconstruct the geometry of complex objects such as lattice telecommunications towers in detail. The main contributions of this study are the development of methodology of data mission planning, data acquisition, processing and demonstration of accuracy required for telecommunication mast inventory.

In the article, the methodology for data acquisition was presented. The research enabled the determination of the optimum UAV flight parameters, ensuring that the data are reliable and valid for the post-processing stage. In addition, the application for UAV operators significantly reduces operational time and increases safety.

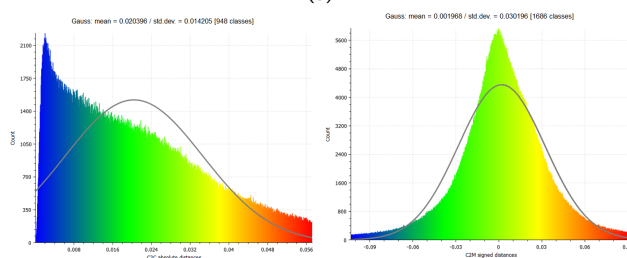
The data used in this study were collected only from existing telecommunication masts. However, the proposed methodology is designed for multi-temporal data acquisition and can therefore provide reference information throughout different stages of a mast's lifecycle. When integrated within an appropriate BIM environment, the 3D models in conjunction with images can be used on various Levels of Development. One limitation during the early design and construction stages is that the reconnaissance mission would need to be based on the planned mast geometry rather than the geometry of the already existing structure. Regarding Level of Detail, the proposed methodology enables the reconstruction of individual mast components and equipment geometry supported by georeferenced images. The most challenging elements such as single cables of small diameter could not be reconstructed either from images acquired from safe distance of several metres, or by the TLS/ULS. While it was not possible to get the 3D representation of such small objects, they were clearly visible on the georeferenced images which also provided additional information on the condition of individ-



(a)



(b)



(c)

(d)

Figure 13: Distance between the DIM point cloud and the ULS point cloud: (a) side view and (c) histogram, and distance between the mesh model and the ULS point cloud for an example object: (b) side view and (d) histogram

ual elements, which is particularly valuable for mast and antennas maintenance. Compared with the proposed image-based approach, TLS can provide very detailed geometric information, but only for lower and more accessible parts of the structure. Limitations related to scanning range and occlusions may prevent complete reconstruction of upper sections of the mast. In the case of ULS, the achieved point density and distribution was insufficient to reli-

ably distinguish the boundaries and shapes of individual devices. Furthermore, ULS-based surveys introduce additional practical challenges related to flight operation, regulatory constraints, and data processing. While active and passive methods provide complementary capabilities, the proposed UAV image-based approach offers a practical balance between geometric reconstruction, visual documentation, automation potential and applicability for repeated inspection of various mast types.

The high accuracy of photogrammetric products (point cloud or 3D mesh model) obtained from UAV images is the basis for recommending the use of this type of data in the development of a Digital Twin of telecommunications towers. A hybrid approach, where both mesh and solid models can be leveraged, enabling the benefits of each to be exploited. A mesh model can also be the basis for a Digital Twin of an object when it is not possible to obtain a complete solid model due to the time-consuming nature of its manual development. In summary, the use of UAVs is justified for inventory, monitoring, and analysis of technical infrastructure, such as telecommunications towers.

Acknowledgements

The research was carried out as part of the project “MAST – Digital twin of mast objects as an innovative inventory service using unmanned aerial vehicles and artificial intelligence” financed by the National Centre for Research and Development, grant no. POIR.01.01.01-00-0426/22.

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