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The potential of UAV-based Laser Scanning for Deformation Monitoring – Case Study on a Water Dam

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ABSTRACT

The use of unmanned aerial vehicles (UAV) in monitoring applications is constantly increasing due to the improvement in sensor technology and the associated higher accuracy that can be achieved. As a result, UAV-based laser scanning is already being used in various deformation monitoring applications such as the monitoring of landslides or land deformations. The main challenges, which also limit the accuracy of the resulting georeferenced point cloud are given by the trajectory estimation, the measurement environment and the flight planning. Difficult conditions and high accuracy demands are especially given for the monitoring of a water dam. While the use of area-based measurements such as terrestrial laser scanning (TLS) is an already established approach for such monitoring tasks, the use of a similar technology on a platform such as a UAV is promising and investigated in this study by acquiring a single measurement epoch at a water dam. In addition to the proposal of a flight pattern for the measurements, the trajectory estimation results are evaluated in detail. Due to critical GNSS conditions, positioning errors lead to systematic shifts between single flight strips. Subsequent optimization with known control points allows the point cloud to be compared to a TLS reference. The difference between the two is shown to have a mean difference of 5 mm with a 9.2 mm standard deviation. This can be considered a highly promising result, especially as the potential for further improvement by using additional targets and sensors (*e.g.* camera) has been identified.

I. INTRODUCTION

Many structures are subject to periodic or even abrupt deformations due to natural and human influences. These include water dams, which are strongly influenced by effects like the annual temperature variations and the water level change. To ensure the safety and stability of such structures, monitoring is carried out using various sensors. The choice of sensor used for monitoring depends strongly on the required temporal and spatial resolution and thus on the expected deformation during the year.

Due to the complexity of dams and their deformation, multiple sensors are usually used to monitor specific parts such as the main barrage, the water reservoir or the stability of the surrounding area. Besides the main task to warn in case of risk, monitoring should also provide conclusions for restoration or possible improvements in future constructions (Scaioni *et al.,* 2018). The typical approach to dam monitoring is divided into sensors capable of continuously measuring local deformation (*e.g.*, tiltmeter, extensometer, inclinometer) and measurements of absolute and relative displacement of the structure and surrounding areas. The second task is usually accomplished by using a geodetic network with various sensors (*e.g.*, total station, GNSS) and individual planned measurement campaigns, as the effort involved is quite significant.

With technological developments in recent years, area-based measurements such as terrestrial laser scanning (TLS) or ground-based SAR (Synthetic Aperture Radar) have increased and led to various advantages, such as the high spatial resolution (Scaioni *et al.*, 2018). The potential of monitoring with TLS has been demonstrated in several studies and, in particular, the area-based approach leads to a more detailed analysis of the structural movement of the dam (Alba *et al.*, 2006; Xu *et al.*, 2018).

In addition to static measurement with TLS, the use and availability of kinematic laser scanning technology have increased in the last decades. Thus, the use of laser scanning on a moving platform with additional sensors for localization on the ground (*e.g.*, cars) or with unmanned aerial vehicles (UAVs) is being developed further. The limiting factor for the use of UAV-based laser scanning for applications such as deformation monitoring has been due to the additional uncertainties resulting from the estimation of the trajectory, describing the position and orientation of the platform over time. This study investigates the potential use of such a UAV system for the task of deformation monitoring of a dam based on a single measurement epoch and is designed to address specific challenges:

- What would be a suitable flight planning and how does it affect the accuracy of the initial trajectory estimate?
- What is needed to handle different flight strips to obtain a consistent and optimized point cloud?

- How can the registration to the same datum with a higher order reference provided by TLS be realized?
- How large is the difference between the captured point clouds from TLS and UAV?
- What are the conclusions and recommendations for further improvements in such an application?

To analyze the use of UAV-based laser scanning for deformation monitoring of a dam, a measurement campaign with TLS reference is presented below. The paper is organized as follows. In Section II, the state of the art of UAV-based laser scanning for deformation monitoring is presented. Then, the measurement campaign is described in Section III. The main part of this study is presented in Section IV with the detailed analysis and summarized in Section V with the conclusion and outlook.

II. UAV-BASED LASER SCANNING FOR APPLICATIONS OF DEFORMATION MONITORING

The use of UAV-based laser scanning has been integrated into various applications, with the focus on monitoring larger areas such as landslides, glaciers, land deformation or applications in forestry. In addition to the use of laser scanning systems, the use of camera sensors on UAVs has also been increasingly addressed in multiple studies. One of the major advantages of aerial-based methods is the ability to deploy a UAV system in hard-to-reach areas, making the surveys both more efficient and safer. One example is the monitoring of power lines and transmission towers, where the stability of the structures is monitored (Lu *et al.*, 2022). Other studies are investigating the use of UAVs with a camera to monitor landslides compared to methods such as TLS (Ćwiąkała *et al.*, 2020; Eker *et al.*, 2018; Jiang *et al.*, 2021).

However, there are also initial studies from recent years on the use of laser scanning systems on UAVs for monitoring tasks. These are also used for landslide monitoring by utilizing estimated roof areas for comparison between different epochs (Zieher *et al.*, 2019). In addition, several studies are evaluating the use to monitor land deformations that may result from mining activities, for example. In combination with TLS and UAV photogrammetry, deformations in the range of several dm can be detected (Jóźków *et al.*, 2021). For land deformation detection, the digital elevation model (DEM) is usually derived to detect deformations from different epochs. This is demonstrated in several examples and typically compared to methods such as TLS or total stations (Moudrý *et al.*, 2019; Wang *et al.*, 2020, Zheng *et al.*, 2022).

Overall, the use of UAV-based laser scanning is mostly integrated for deformations with a magnitude of cm-dm and not for higher requirements as might be necessary for a dam analysis. Since the use of TLS is already a common method for dam monitoring, in which the analysis is based on the resulting point cloud (Alba *et al.*, 2006; Scaioni et al., 2018; Xu *et al.*, 2018), a similar approach on a UAV is well feasible but neglected so far due to the lack of accuracy. For these reasons, and because of the advantages of UAVs, their use for dam monitoring is investigated below.

III. MEASUREMENT CAMPAIGN

The measurement campaign consists of two parts, divided into the generation of a reference point cloud based on the terrestrial laser scanning (TLS) measurements and the acquisition of two similar flights with the UAV-based laser scanning system. Special UAV targets are used below to register the UAV system derived point cloud to the TLS reference. Therefore, the datum definition for comparisons is defined by the TLS registration with a local coordinate system. Since the evaluation in this paper analysis especially the precision of the UAV point cloud, the capability of direct georeferencing is only used for the trajectory processing. In the following, Section III A will first describe the water dam (Figure 1). Section III B discusses the TLS measurement performed, including the estimation of the target centers, which provide the local datum for all comparisons within the analysis. Furthermore, Section III C presents the UAV system used, including the integrated sensors, the flight parameters, and the flight pattern performed during the measurement.

Figure 1. Water dam as monitoring object.

A. *Study area water dam*

Deformation monitoring of dams is a necessary and proven procedure to ensure the stability of these structures in the long term. There are different techniques and sensors suitable for continuous monitoring or specific control measurements. For the analysis of the use and thus monitoring with a UAV-based laser scanning system, the study area with the dam shown in Figure 1 was selected. This dam, like most dams, is subject to annual deformations that need to be monitored regularly. The deformations are caused by the changes of the water level, but mainly by the temperature variations during the year. Therefore, this object is well suited for the evaluation of the survey using the UAV-based laser scanning system. The dam is approximately 27.7 m high and has a crest length of 152 m. During the measurement campaign in June 2021, the surrounding area was also heavily covered with vegetation, which is why flight planning, in particular, proved to be challenging under very difficult conditions.

B. *Reference point cloud and datum definition*

The assessment of the UAV-based laser scanning is mainly done in comparison to a reference point cloud acquired with TLS. The TLS measurements and thus the different stations in the study area are shown in Figure 2 with the corresponding TLS targets required to register the different stations to each other. The laser scanner used is the Leica ScanStation P50 and the targets are BOTA8 (Bonner target with 8-fold pattern) developed for high accuracy demands using target-based registration (Janßen *et al.*, 2019). The different scans for stations 1-7 were measured with a scan resolution of either 1.6mm@10m or 3.1mm@10m. Based on the estimate of the target center of each TLS target, registration in Leica Cyclone was performed with an RMS of less than 1 mm for the included targets. In addition to the TLS targets, the target centers of the larger BOTA8 targets (0.8 m x 0.8 m), also labeled as UAV targets in Figure 2, are estimated for the registration of the UAV point cloud. Since the point cloud of one station is sufficient for the following point cloud comparison, only station 7 is used since it provides the best view of the middle part of the dam.

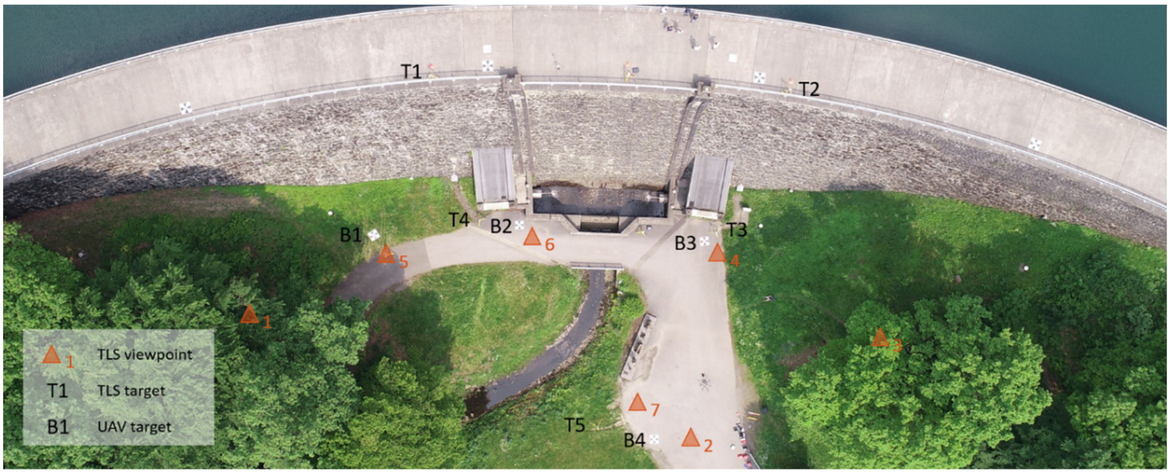

Figure 2. Overview of the study area with locations of TLS stations, TLS targets and UAV targets.

C. *UAV-based acquisition of the water dam*

The UAV-based laser scanning system used to survey the dam consists of a DJI Matrice 600 platform with a RIEGL miniVUX-SYS, as shown in Figure 3. Integrated into this is a high-quality Trimble APX-20 UAV IMU/GNSS combination for estimating position and orientation over time defined as the UAV's trajectory. The additional full waveform 2D laser scanner RIEGL miniVUX-2UAV is used for object detection. By combining it with the trajectory a georeferenced 3D point cloud can be derived. The first part of the trajectory estimation is performed by using an additional GNSS master station for differential GNSS processing and subsequent sensor fusion with the IMU data using a Kalman filter. The master station is a virtual reference station (VRS) provided by SAPOS, which gives GPS, GLONASS, BeiDou, and Galileo observations. All processing is done in Applanix POSPac UAV software, which calculates a smoothed trajectory with additional accuracy metrics for analysis. The laser scanner has a maximum laser pulse repetition rate of 200 kHz and a field of view of 360°. When used at the dam, the field of view results in good scanning geometry as it is flying parallel to the dam. The only limitation is the obstruction by the rotor arm, so the field of view to be processed is limited to 80° - 280°. The subsequent combination of the estimated trajectory with the laser scans is done in RIEGL RiPROCESS, which also includes the additional sensor calibration. The error budget, and thus the accuracy of the UAV system, can be also divided into the trajectory and laser scanning parts and are shown in Table 1.

Table 1. Error budget of the UAV-based laser scanning system according to the manufacturer (Riegl, 2020)

Accuracy	Values
Trajectory estimation – position vertical [m]	< 0.10
Trajectory estimation – position horizontal [m]	< 0.05
Trajectory estimation – roll & pitch [deg]	0.015
Trajectory estimation – heading [deg]	0.035
Laser scanner [m]	0.015

Regarding the accuracy of the product with a georeferenced 3D point cloud, the crucial part is given with the estimation of the trajectory (Dreier *et al.*, 2021). According to the manufacturer, the accuracy for the position is < 0.05 m for the horizontal direction and < 0.10 m for the vertical direction. Furthermore, the orientation is about 0.015 degrees for roll & pitch and about 0.035 degrees for heading. Compared with the accuracy of the trajectory, the accuracy of the laser scanner is relatively high at 0.015 m. The given quantification depends especially on the measurement conditions like GNSS constellation and flight parameters. Investigations by Dreier *et al.* (2021) have shown even better results for the use of this UAV system, especially regarding the precision. This is also advantageous because the inner geometry of the UAV point cloud is more important for the application than the georeferencing, since it is registered to the local control points. Therefore, the potential of a direct georeferenced point cloud is not exploited in this study, although it might be useful for future projects.

Figure 3. UAV system with the RIEGL miniVUX-SYS.

Flight planning and execution were performed using UgCS software according to the flight pattern shown in Figure 4. Since a detailed representation of the entire dam is required, the flight is conducted with parallel flight strips at ascending heights, starting at the lowest point. This flight pattern is similar to a facade scan typically performed for image-based acquisition with a UAV. Since the laser scanner measures in a plane orthogonal to the flight direction, the scan geometry is advantageous. However, the flight pattern chosen is very unusual for UAV-based laser scanning with no cross flights or flight curves instead of sharp turns at the end of a flight strip. Unfortunately, with this object and the surrounding conditions with many trees, it is not possible to do otherwise. The flight parameters used are the flight speed of 0.5 m/s, a lateral distance of about 10 m from the water dam, and successive strips with flight heights of 5 m, 10 m, 15 m, 20 m, 25 m, 30 m, 40 m and 50 m. Using the laser scanner's line speed of 53.8 lines per second, the average point density is approximately 3650 points/m^2, although this is not entirely uniform because the distance to the dam is not identical for each flight strip. As described in this part, the final point cloud is calculated in RIEGL's RiPROCESS software and the different flight strips are calculated individually. In the subsequent analysis of the data, the RiPRECISION tool is also used to perform various optimization strategies for an improved point cloud. The possibilities and procedures will be discussed in the next part.

IV. Analysis

The objective of this study is to compare and verify the suitability of UAV-based laser scanning for applications such as deformation monitoring. In the following analysis, the point cloud obtained with the UAV is checked for consistency in Section V A. This is done by relating the different flight strips to each other and attempting to clarify the difficult conditions for trajectory estimation. The optimization of the UAV point cloud using RIEGL's software follows in Section V B, the comparison with the TLS reference is performed in Section V C. using the UAV targets for registration. Several aspects are investigated in comparison to the TLS point cloud. First, the spatial resolution of the UAV point cloud and thus the level of detail is highlighted. Next, the inner geometry of the UAV point cloud is analyzed to determine how it compares to the reference.

A. *Analysis of the point cloud acquired with the UAV*

The complete point cloud from the UAV-based laser scanning system is initially split into separate point clouds from the individual flight strips starting at a flight height of 5 m. Since the trajectory estimate will likely will contain larger uncertainties after the 180° turn and upward movement, the separation into strips is reasonable. Before evaluating the computed point cloud, the prevailing measurement conditions should be highlighted, focusing on the GNSS conditions.

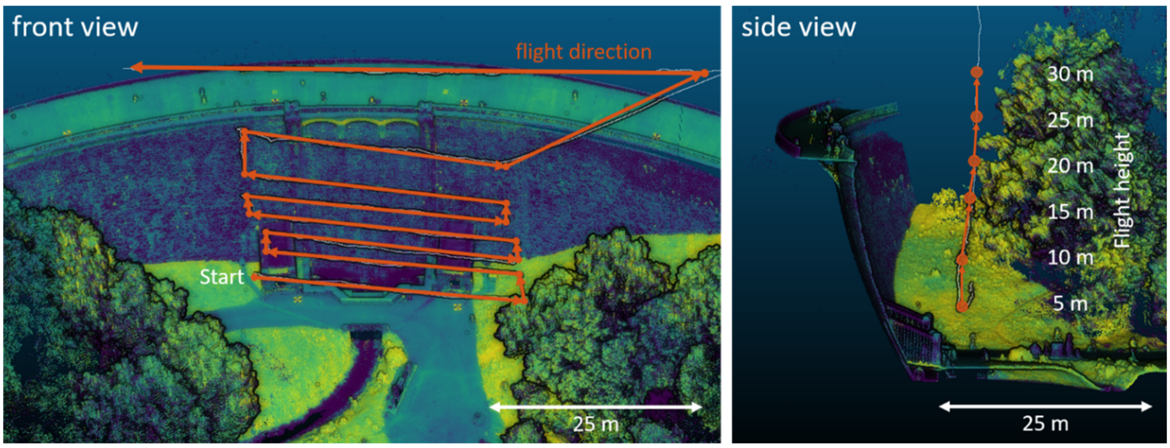

Figure 4. Flight pattern performed for the UAV measurements with a front view (left) and side view (right).

Figure 5 shows the satellite visibility and PDOP values in relation to each flight strip. With the additional heading of the UAV in the top plot, the individual flight strips can be identified with the 180° turn included. The time series showed starts with the first flight strip at 5 m height to the fourth flight strip at 20 m flight height. It can be seen that the number of satellites for the first strip is very low with 10-13 satellites and a corresponding PDOP above 2. In addition, there are several signal interruptions of individual satellites, which leads to smaller jumps in the number of satellites and also the PDOP. For this reason, it is assumed that the signals are partially obscured by objects or vegetation and thus there is a high probability of outliers. In addition, the measurement environment has a very high probability of the occurrence of errors such as far-field multipath and diffraction, which cannot be safely handled in the positioning algorithm (Zimmermann, 2020). These aspects with a small number of satellites, the very error-prone environment, and poor satellite geometry lead to a very difficult task for trajectory estimation, which may involve higher uncertainties compared to better conditions. The challenging environment described above improves with increasing UAV height, although the situation at 20 m seems to be sufficiently good considering the number of satellites and the corresponding PDOP. However, since a continuous high-resolution point cloud is desired, low flight heights are also taken into account. Since the evaluation of the accuracy of the trajectory estimation itself is not possible, the point clouds of individual flight strips are used for investigation in the following part.

The point clouds from 5 flight strips taken at a flight height of 5-25 m are shown in Figure 6, with the combined point cloud on the left and two selected areas on the right. The point cloud on the left, colored with intensity values from the laser scanner, provides an initial overview of the level of detail that can be captured by the UAV system. Inspecting the detail view in the right part of the figure, the uncertainty of the trajectory estimation can be seen. Each flight strip is individually colored and systematic errors between them become visible. These can be explained by the unusual flight pattern and the critical GNSS conditions. However, initial conclusions can also be drawn from the offsets shown between the flight strips. The top view of a part in the center of the water dam shows a shift of several cm-dm in the horizontal position of the individual strips with respect to each other without additional tilting. The same applies to the part in the lower right area shown from the side view. This angle of view primarily shows a shift between the flight strips in the vertical direction without any additional tilting of the flight strips with respect to each other. Finally, this leads to the conclusion that due to the critical environment and conditions for GNSS positioning, systematic errors in the position in the global coordinate system cause offsets between different flight strips.

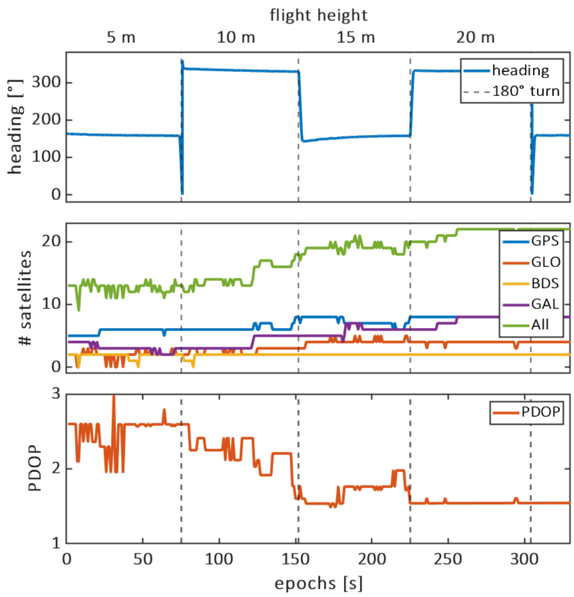

Figure 5. GNSS condition for the first four flight strips of one flight with corresponding heading and 180° turns.

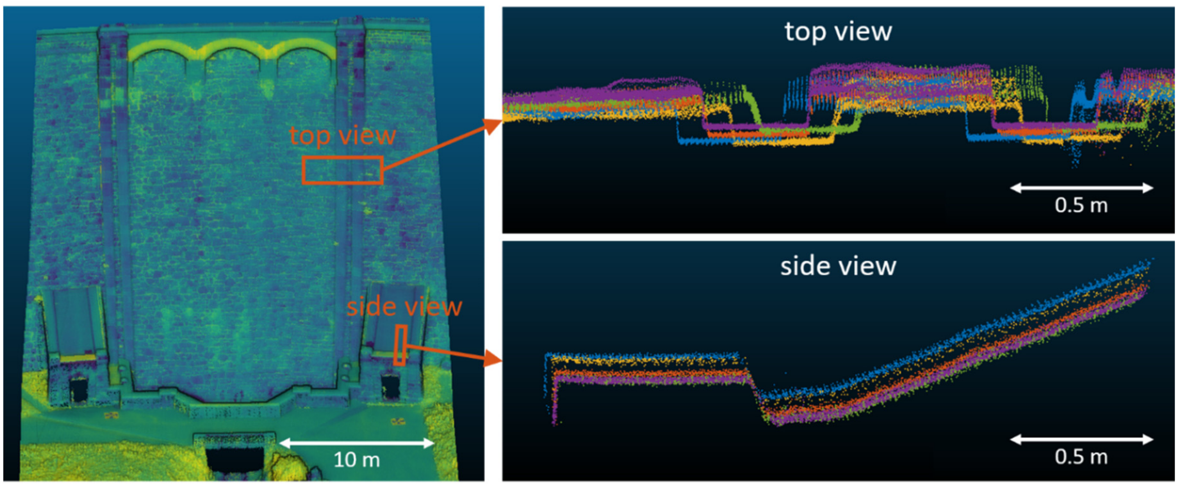

Figure 6. UAV point cloud from 5 different flight strips (different colours) with side and top view for specific areas.

To verify the inner geometry of multiple flight strips, UAV targets B2 and B3 are used to compare the 3D distance between the two target centers (see Figure 7). Since there are no other UAV targets measured with good scan geometry, only one distance is calculated for each flight strip and compared to the reference distance derived from the TLS point cloud. The difference in calculated distance from the reference is shown for flight strips 1-6, and in this case also for the two separate flights with similar flight patterns, to demonstrate the repeatability of an independent measurement. The differences are all less than 3 cm and, in most cases, even less than 2 cm. In particular, the second flight shows good results for flight strips 3-6 with differences below 1 cm. This investigation shows the high precision and thus the consistency of the inner geometry of the individual flight strips. From the previous detailed evaluation of the derived point cloud, several conclusions can be drawn. First, the critical conditions for GNSS positioning can already be suspected by examining the number of satellites and the resulting PDOP values. Furthermore, the atypical flight pattern could lead to additional uncertainties in the trajectory estimation. These assumptions are supported by looking at the point cloud and the systematic offsets between the flight strips. Nevertheless, the inner geometry seems to be almost unaffected by this, and therefore the most important information for the monitoring task is preserved.

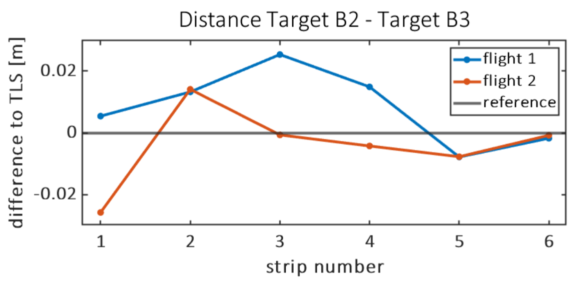

Figure 7. Comparison of distances between Target B2 – B3 from two UAV flights compared to TLS.

B. *Optimisation of the point cloud*

There are various options to improve the quality of the derived point cloud and in particular the consistency between different flight strips. For this task, the RIEGL software RiPRECISION is used, which is able to perform different optimization strategies to correct the trajectory based on measurements from multiple strips. Besides the automatic identification of areas and features to improve the point cloud, it is also possible to introduce control planes or points to adjust the trajectory. The performance of the optimization procedure has been demonstrated in several studies and can be classified as a reliable tool if the object and also a beneficial flight pattern are chosen (Dreier *et al.* 2021). For the evaluation of the optimization and also the following comparison with the TLS reference, only the second flight is used, since the results are very similar. Besides the features, which are automatically detected by RiPRECISION, the control points for the UAV targets B2, B3 and B4 are also included in the optimization. The result is shown in Figure 8 for the example of two different flight strips in orange (10 m flight height) and blue (20 m flight height). In this case, the visual inspection shows a consistent point cloud that fits in both horizontal and vertical directions. There are only local variations between the flight strips, which are of the order of less than 1 cm. For clarification, the improvement is shown only for two strips, because the optimization does not work for all contained strips of the dataset. There are still deviations especially in the horizontal direction, as can be seen in the upper right part of Figure 6. The height offset on the other side is completely eliminated since the ground can be used for adjustment.

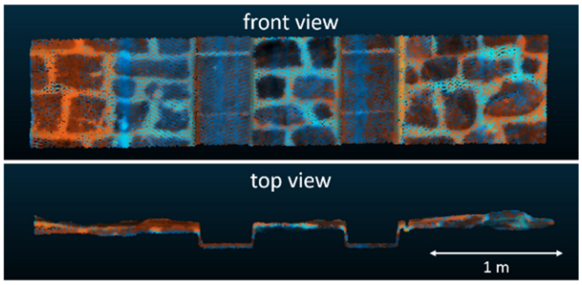

Figure 8. Two flight strips with 10 m (orange) and 20 m (blue) flight height.

The reason for the remaining offsets is the difficulty in capturing the object and the lack of structures such as concrete walls or roofs to enhance the point cloud. Moreover, this is usually achieved by additional flight strips in the cross direction, which can fix or correct the point cloud in the direction of the water dam. These facts influencing the optimization process are one of the main challenges when we consider an object like the dam, where the structure and scan geometry is pretty much the same for the whole data set.

Therefore, several aspects can already be summarized based on the point cloud acquired by the UAV. Trajectory estimation is the most critical part of the processing and also the most error-prone. This can be corrected by different optimization strategies in post-processing, for example by including control objects. Since this approach cannot correct the entire data set with multiple flight strips, in this case, additional aid for trajectory estimation is recommended. This could be done by integrating additional information from simultaneously acquired images or by introducing additional artificial objects to adjust the trajectory. For the following comparison with the TLS, only single flight strips are used to show the potential of the derived UAV point clouds without considering errors that might have been preserved due to uncorrected offsets.

C. *Comparison with TLS*

The optimized point cloud derived from the UAV system is compared with the reference point cloud measured with TLS described in Section III B. In order to apply a method of point cloud comparison, the UAV point cloud must be transformed into the local coordinate system and thus into the datum definition given by the TLS. The Helmert transformation between the two systems is based on the UAV target centers estimated from both data sets. Since the scale of both point clouds is well defined, only the parameters for three translations and three rotations are applied. A critical aspect of this transformation is the small number of UAV targets, which leads to a lack of redundancy as usually recommended. Nevertheless, the transformed point cloud derived with the UAV system and analyzed in the following fits the TLS point cloud in an order of magnitude that the transformation parameters can be evaluated as sufficiently accurate.

A first comparison of the two results is shown in Figure 9 with a detail of the middle part of the dam. The left part shows the UAV point cloud and the right part is the TLS point cloud, both colored by intensity value. This visual inspection should highlight several aspects if UAV-based laser scanning is to be considered a viable alternative. First, the geometry of the dam with stones and joints in between can be seen in similar detail at the scale shown. In addition, the direct transition between the two demonstrates the potential of the UAV system in being able to accurately reproduce the geometry, at least from this perspective. Overall, these inspections show the potential and precision of the UAV point cloud, even though they are only done on a visual basis. To quantify the differences between the two point clouds, the method Multiscale Model to Model Cloud Comparison (M3C2, Lague *et al.*, 2013) is applied and the result is shown in Figure 10. For this comparison, the flight strip with a flight height of 20 m is again used, covering only the central part of the dam. Besides the colored parts with a M3C2 distance, the gray part represents only the TLS point cloud used. The distribution of differences shown on the right results in a mean difference of +5 mm and a corresponding standard deviation of 9.2 mm. Based on the error budget shown in Table 1, the differences can be considered better than expected. The combination of the uncertainties from the trajectory estimation with the additional uncertainty due to the laser scanner supplied by the manufacturer is significantly higher than in the comparisons shown.

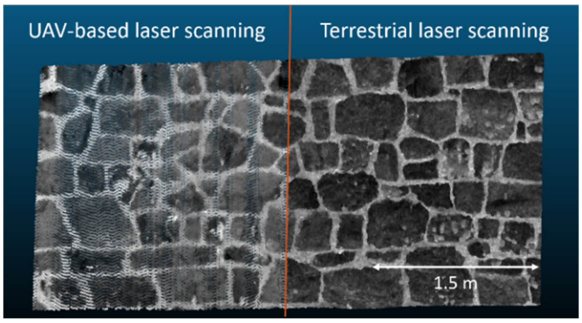

Figure 9. Detailed part of the point clouds coming from UAV-based laser scanning and TLS.

Nevertheless, the comparison shows systematic effects in different areas of the dam that can be attributed to the precision of the trajectory, which cannot be detected by the evaluation steps done before. Another possible uncertainty contributing to this comparison is given with the Helmert transformation of the UAV point cloud to the local datum where only three control points were used. Since an incorrect set of transformation parameters would lead to even larger systematic differences between the two point clouds, this can be neglected. Overall, the M3C2 comparison produced good results for the challenging measurement conditions and highlighted several aspects with potential for improvement.

V. CONCLUSION AND OUTLOOK

In this study, we presented the use of UAV-based laser scanning for the task of deformation monitoring using a single measurement epoch of a water dam as an example. With the presented approach for the measurement, the analysis of the trajectory with corresponding flight strips and the final comparisons between the UAV point cloud and the TLS reference, several conclusions and challenges can be drawn.

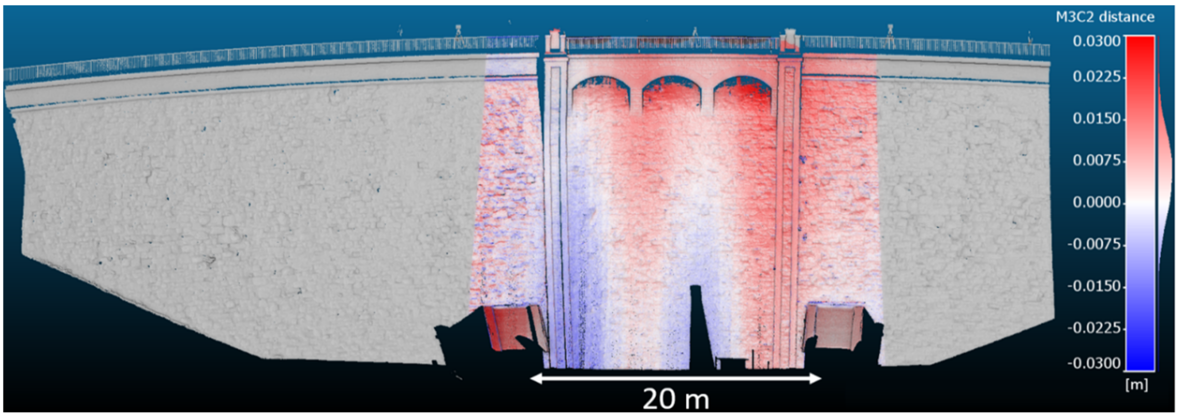

Figure 10. M3C2 distances between UAV point cloud from the 20m flight strip and TLS.

First of all, the environment and flight planning for such a dam were very challenging and highly error-prone, especially considering the GNSS conditions and their impact on the trajectory estimation. Therefore, optimization algorithms for the UAV point cloud are highly recommended to improve the consistency of the different flight strips. However, the object of the dam and the corresponding flight pattern is very challenging for the available optimization methods, so it was not always possible to correct every flight strip as desired. In this study, the subsequent transformation to an identical datum for comparison with TLS could contain additional errors that can be easily avoided. The final results from the comparison are very promising considering the poor measurement conditions and the uncertainties included in the processing chain. These conclusions can be formulated in the following aspects:

- The environment imposes high demands on the flight planning, but also on the resulting measurement conditions, especially on the GNSS reception.
- An improvement of the trajectory estimation is necessary by using the strip optimization between several flight strips.
- The optimization should be supported by additional artificial objects such as targets, which can also be used for accuracy assessment or comparison to other measurements like TLS.
- The integration of additional sensors that support trajectory estimation, such as cameras, is conceivable.
- For comparisons with TLS or other sensors, registration should be solved separately or known in advance.

The conclusions presented are mainly related to the trajectory estimation part or the subsequent optimization part to achieve higher precision of the resulting point cloud. Since the shown comparison of the point clouds from the dam already gives a mean difference of 5 mm with a standard deviation of 9.2 mm, even better results can be expected for further new measurements with improved planning. In particular, the use of additional UAV targets that can be included in the optimization process will be tested in the future.

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