An Innovative Image-Based Surveying Approach for Globally Referenced Remote Point Measurements

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SUMMARY

Mapping with unmanned aerial vehicles (UAV) and autonomous driving are megatrends that bring new challenges and opportunities also for surveying applications. In the last years, dramatic advances in computer vision and artificial intelligence have opened up new perspectives in positioning and reality capture systems. These applications rely upon an accurate and robust determination of the absolute six degrees of freedom (6DoF), mainly combining global navigation satellite system (GNSS) and inertial navigation system (INS). Including GNSS has the main advantage of accurate 3D positioning directly in a global reference system. Additionally, the integration of other measurement systems such as camera-based visual inertial systems (VIS), LiDAR, and scanning will benefit from the precise attitude information and globally referenced positions.

This paper aims at analyzing the potential and performance of combining simultaneous image capturing and absolute 6DoF information for surveying applications. The 3D position and attitude estimation by means of a GNSS/INS system is consolidated with a camera and computer vision algorithms. This image-based surveying approach enables accurate remote point measurements by fusing GNSS RTK with terrestrial photogrammetry directly in the field, providing globally referenced positions with centimeter-level accuracy. Photogrammetric surveying and scene documentation can be performed conveniently in a global reference system. Additionally, high-precision survey-grade measurements becomes possible in GNSS degraded and denied locations enhancing productivity and user experience.

In this study, global position and attitude information are combined with computer vision algorithms and camera captures to measure points in images. The results are compared against a reference field with a higher order of accuracy. Representative tests were carried out by considering various camera-to-object distances and trajectories varying in length and geometry to evaluate the accuracy and reliability of this novel sensor fusion platform. The outcomes show that the combination of photogrammetry with a GNSS/INS system offers enormous potential in land-based surveying applications where globally referenced measurements are demanded within the shortest time.

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1. INTRODUCTION

Using GNSS RTK (real time kinematic), the rover position is measured at the antenna phase center, whereas the tip of the surveying pole is placed at the target point on the ground. In conventional RTK surveying there is a need to level the pole to reduce the phase center position to the pole tip position. In the last years, technical innovations enabled accurate measurement of the pole tip position even when a pole is tilted. Such surveying instruments, as the Leica GS18 T, are based on a sophisticated GNSS and INS (inertial navigation system) integration to enable calibration-free tilt compensation RTK measurements. The INS computes the tilt angle relative to the vertical and the direction of the tilted pole (with respect to geodetic north) in real time which are used to compensate for the tilted pole. Such innovations speed up the surveying workflow by helping the surveyor measure faster and improve RTK availability in difficult environments. Points as building corners that were previously inaccessible with a vertical pole can now be measured with centimeter-level accuracy in tilt compensation mode (Luo et al., 2018a,b). However, using a GNSS rover mounted on a pole for a surveying workflow still has some limitations:

- Requires physical access – the pole tip has to be placed on the target point, which compromises safety in dangerous surveying areas (e.g. street with heavy traffic)
- Demands time – placing the pole tip on the target point needs time, which sums up if a large number of points have to be measured
- Inaccessibility of the site – certain areas may have limited access or are not reachable with the pole tip directly (e.g. points on a roof or in a trench)
- Obstruction of GNSS signal – in some areas high-precision positioning with GNSS RTK may not be possible

There is a demand of developing a surveying approach that overcomes these obstacles and enables surveying with a positioning quality comparable to GNSS RTK while increasing availability and enhancing the workflow.

In the last years, also dramatic advances in computer vision have opened up new perspectives in positioning and reality capture systems. Camera-based visual inertial systems (VIS) rely upon accurate camera pose (position and orientation) determination and will benefit from the integration with a GNSS/INS system. Additionally, the integration with GNSS has the main advantage of estimating an accurate position directly in a global reference system.

By combining a camera module with a GNSS rover, georeferenced remote points can be measured in near real-time with the use of photogrammetry (Siercks et al., 2019). Such surveying systems belong to the category "imaging rover" and it was shown in

Baiocchi et al. (2018) and Cera and Campi (2017) that when using such technology in the field of terrestrial photogrammetry, there is potential of greater efficiency and operational simplifications.

This paper presents a new image-based surveying approach by using a multi-sensor system combining GNSS, inertial measurement units (IMU) and a camera module. The system utilizes precise IMU measurements from industrial-grade micro-electro-mechanical sensors (MEMS) and GNSS observations to estimate georeferenced camera poses. Capturing images along with accurate georeferenced camera poses open up a variety of possibilities for surveying applications. The main advances are:

- Increase productivity – capturing a large amount of points within a short time
- Increased availability – measuring points in GNSS degraded and denied areas where alternative solutions (e.g. total station) would be time consuming and cost intensive
- Increased safety – capturing points that cannot be easily accessed without putting the surveyor in risk (e.g. across a street with traffic, inside a trench)
- Increased flexibility – capturing the scene as fast as possible and decide later what should be measured

The presented surveying approach combines accurate position and orientation of the rover with camera captures which are simultaneously recorded while passing the scene of interest. As illustrated in Figure 1, while moving along a trajectory, the sensor captures an image at epoch t_i and estimates its position and attitude for the same epoch in real time. If an object is captured from different perspectives and at different epochs (t_i, t_{i+1}, t_{i+2}, ...), the position of the object can be photogrammetrically determined in the images right after the scene has been recorded. This image-based surveying approach enables near real-time photogrammetric point measurements without any additional post-processing steps or need of ground control points.

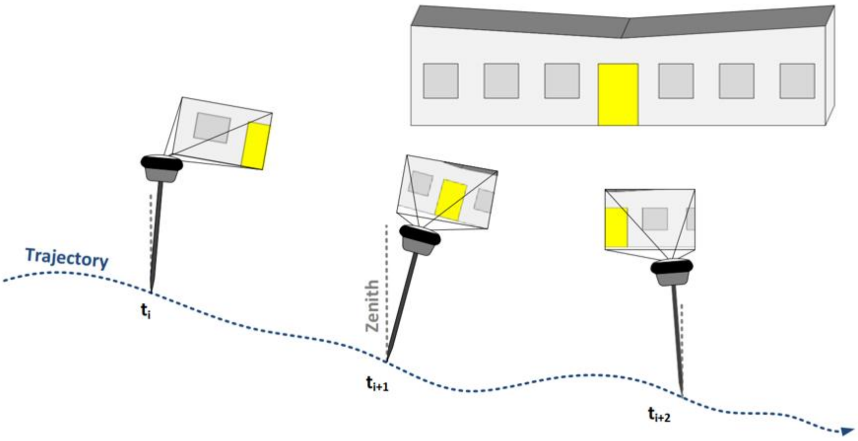

Figure 1 Schematic illustration of the measurement workflow of the presented image-based surveying approach, where images are recorded at epochs (t_i, t_{i+1}, t_{i+2}, ...) while passing the scene of interest.

2. CAMERA POSE ESTIMATION

The proposed image-based surveying approach relies upon an accurate and robust determination of the absolute 6DoF of the sensor. Figure 1 shows that images of the same scene are captured from different perspectives and at different epochs. The core element of this surveying method is to have accurate camera pose information corresponding to the epochs when the images were captured. The estimation of the final precise camera poses succeeds in two steps as presented in Figure 2. First, the initial camera poses are determined by means of GNSS/INS integration. Simultaneously, features are extracted from the collected images and tracked from one image to the subsequent one. Afterwards, the extracted features and the initial estimations of the camera poses are used in a bundle adjustment to optimize the camera pose determination.

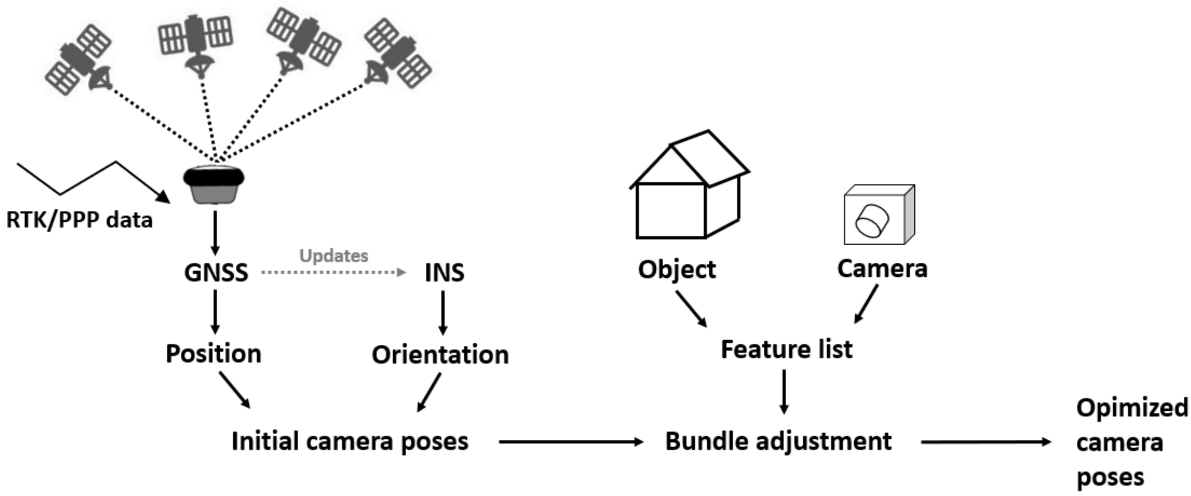

Figure 2 Flow diagram representing the optimization process of the camera pose estimation.

2.1 GNSS/INS integration – initializing the pose

Combining measurements from GNSS and IMU is a well-established sensor fusion technique to estimate the 6DoF (Jekeli, 2001; Titterton and Weston, 2004; Groves, 2013). The GNSS/INS integration takes advantage of the complementary characteristics of the two navigation sensors. Such GNSS/INS combined navigation systems have existed in the aerospace industry for many years and are now available also for surveying applications (Dusha, 2017; Luo et al., 2018a,b).

The choice on the correction type applied to obtain a high-precision GNSS position (either RTK or precise point positioning PPP) also defines the underlying coordinate frame with the advantage that no reference frame transformation of the photogrammetric measurements (i.e. using ground control points) is needed afterwards. The subsequent GNSS/INS integration provides georeferenced position and orientation of the sensor which is used for the initial camera pose information. Depending on light conditions of the captured scene, every image has got a certain exposure time, which varies within a few milliseconds. The dedicated timestamp of an image is the middle of the exposure time and the camera pose has to be estimated at the same epoch to ensure time synchronization.

2.2 Bundle adjustment – refining the pose

The initial estimation of the pose obtained by processing GNSS and INS observations is refined by applying advanced computer vision algorithms. During the course of image capturing, the sensor is simultaneously extracting features from the images by means of an interest point detection algorithm. A feature is a distinctive image point such as local extrema (maxima or minima) which is a potentially suitable candidate for image-to-image matching (Luhmann et al., 2014). Corresponding features are generated to establish the geometric connection between the images. Afterwards, a bundle adjustment algorithm iteratively optimizes the geometry between camera poses and the 3D object points computed from the features. The results are refined camera poses at the timestamps when the images were captured.

3. IMAGE POINT MEASUREMENT

As mentioned in Kraus (2007), the position, orientation, shape and size of an object can be reconstructed from pictures. The coordinates of object points, which are captured in images, can be obtained by applying photogrammetric approaches without a physical contact to the surveying device. This enables remote point measurements out of images, which is widely used in the field of photogrammetry.

3.1 Photogrammetric forward intersection – measuring object points

In order to measure the coordinates of object points remotely, the recorded images and their corresponding optimized camera poses are required. If an object point is captured in two or more images, the coordinates of the object point can be determined by applying methods of close-range photogrammetry (Kraus, 2007). As an example, Figure 3 schematically illustrates the process of measuring two object points P_{10} and P_{20}. These points are captured in three different images (KF0, KF1 and KF2) and the associated camera poses (O_0, O_1 and O_2) are available. By selecting the corresponding image coordinates of the object point in KF0, KF1, and KF2, the coordinates of P_{10} and P_{20} are determined by means of forward intersection. Since this image-based surveying approach directly estimates the camera poses in a globally referenced frame given by GNSS, the determined object coordinates are automatically georeferenced in the same coordinate system.

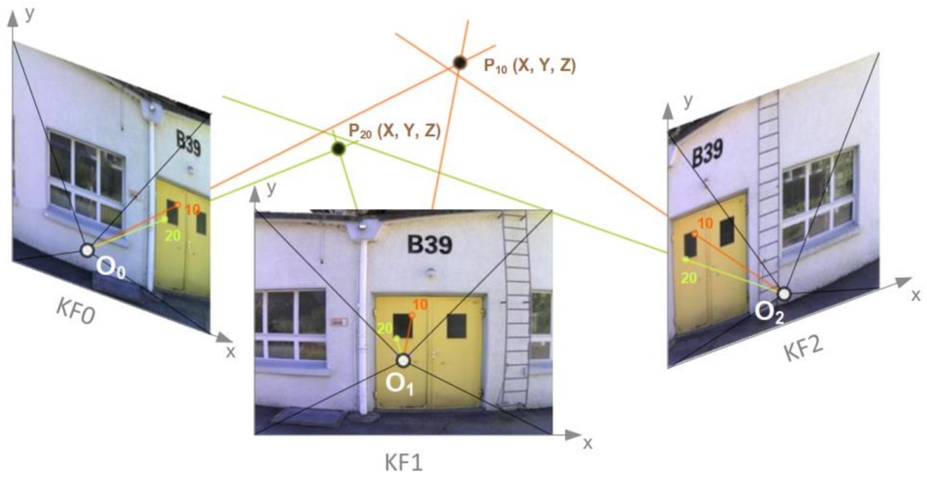

Figure 3 Schematic illustration of the photogrammetric forward intersection to measure object points P_{10} and P_{20}.

3.2 Matching – finding corresponding points

A key element of the photogrammetric forward intersection is to select the image coordinates of the object point in several images as observables. To support the user, the proposed image-based surveying approach automatically searches for corresponding image coordinates of the object. After selecting the object point by the user manually in one image, the matching algorithm extracts a reference image patch around the defined image point. This image patch is a subset of the image and describes the pattern in the immediate vicinity of the selected image point (Figure 4). In the epipolar geometry, an epipolar line is the intersection of an image with the epipolar plane and connects corresponding points in different images (Hartley and Zisserman, 2003). The matching algorithm searches in different images along the epipolar line for similar patterns as defined by the reference image patch and is able to extract image coordinates of the same object point from different images automatically.

To summarize the whole workflow, the user selects an object point in one single image where the object point is best visible. The matching algorithm autonomously detects the selected point in up to five images where the object is visible and identifiable. A minimum parallax between neighbor images is considered to ensure a good intersection angle. Finally, the globally referenced coordinates are computed using photogrammetric forward intersection. This approach allows measuring object points via a single click, improving usability and productivity.

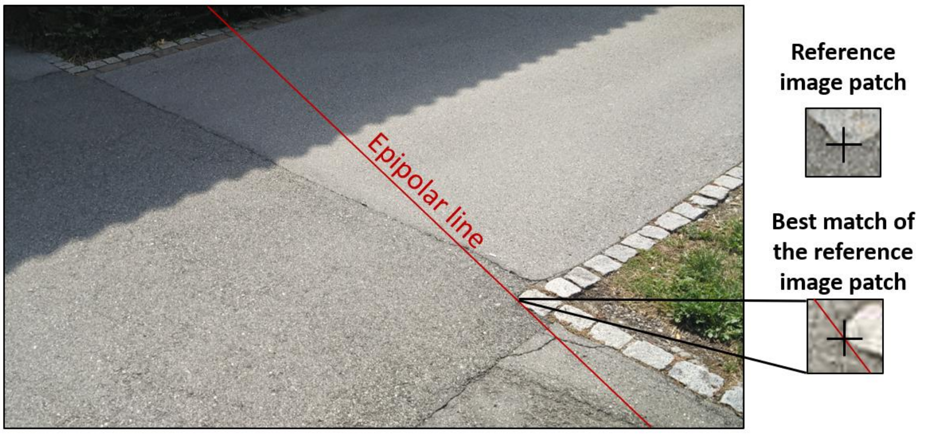

Figure 4 The matching algorithm searches for the best match of the reference image patch along the epipolar line to find the corresponding points.

3.3 Performance analysis

Representative tests were carried out to evaluate the accuracy and reliability of this new image-based surveying approach. A total of 149 image groups were collected, where an image group is a set of images and camera poses of the same scene. All datasets show different trajectories in terms of geometry, dynamic and environmental conditions while walking with the system close to the object of interest to record the scene. Within these 149 image groups, 1075 object points were measured. The collected images include realistic use case scenarios considering various camera-to-object distances, difficult GNSS environments (e.g. due to multi path) and different light conditions. Figure 5 presents some examples of the surveyed objects on a roadside and on a building facade.

Figure 5 Examples of the measured object points such as photogrammetric markers, stone edges, window corners, concrete edges and pipes.

Different object points such as stone edges or facade points were measured remotely from different camera-to-object distances (2 m - 10 m). The estimated coordinates were compared against a reference field, where the reference coordinates were determined independently using a total station and with a significantly higher accuracy.

3.3.1 Global accuracy

As mentioned in section 2.1, the presented image-based surveying method provides coordinates of remote points in the same global coordinate system as defined by GNSS. The term global accuracy includes all measurement errors as well as uncertainties in the pose estimation and uncertainties realted to the photogrammetric forward intersection. It represents the expected overall accuracy when measuring remote points with this image-based surveying system. Figure **6** shows the statistical distribution of the 3D errors from all 1075 remote point measurements. About 80% of the 3D error are within 5 cm, where the camera-to-object distance ranges from 2 m to 10 m. The median 3D error is 3.3 cm and 50% of the 3D errors are between 2.2 cm and 4.6 cm.

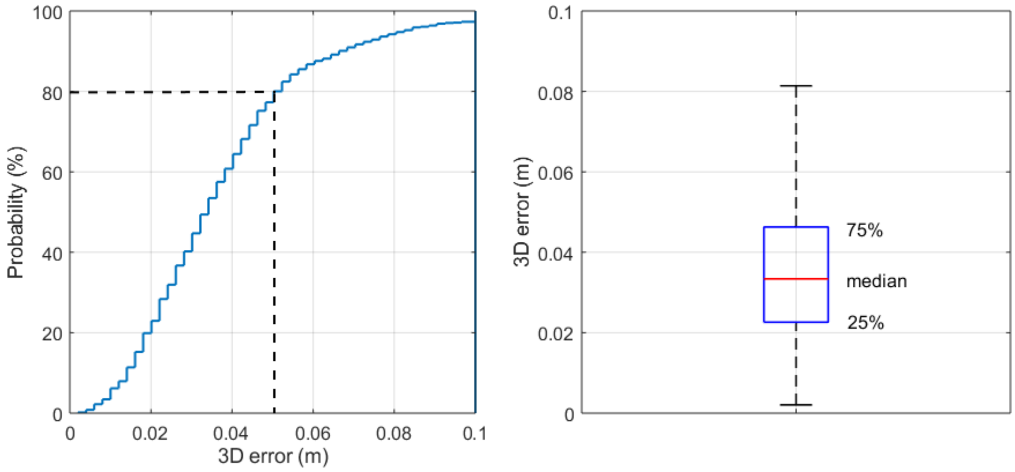

Figure 6 3D error distribution of 1075 image-based remote point measurements shown in empirical cumulative distribution function (CDF) and boxplot.

Table 1 Error statistics of 1075 image-based remote point measurements in meter (see Figure 5 for examples of measured object points).

	Total (3D)	Horizontal (2D)	Height (1D)
Mean	0.036	0.025	0.020
Std. dev	0.018	0.015	0.014
RMS	0.040	0.029	0.025

Table 1 provides the error statistics of the image-based remote point measurements. The 2D and 1D RMS error are 2.9 cm and 2.5 cm, respectively. The overall 3D accuracy amounts to 4.0 cm. The results obtained in this study show that this image-based surveying approach is able to provide cm-level accuracy and can be applied in various high-precision surveying tasks.

3.3.2 Reliability

Besides the coordinates of the object point, the algorithm also computes a measure for the quality of the coordinates. The coordinate quality (CQ) is an indicator for the uncertainty of the measured point. The CQ value is derived such that there is approximately a 68% (1-sigma) or

99% (3-sigma) probability that the computed position deviates from the true position by less than 1×CQ or 3×CQ, respectively. The term reliability is computed as the percentage that the position errors are smaller than one or three times the corresponding CQ value. Considering all 1075 remote point measurements, Table 2 provides the 1×CQ and 3×CQ reliability values.

Table 2 Reliability of 1075 image-based remote point measurements in percentage

	Total (3D)	Horizontal (2D)	Height (1D)
Error < 1×CQ	76.5	79.3	49.2
Error < 3×CQ	99.6	99.2	88.4

Looking at Table 2, the computed reliability in real use case scenarios confirms that the estimated CQ indicator is a reliable measure of the uncertainty of the image-based surveying system. The test data depicts that the 3D error of a remote point measurement is less 3×CQ with a probability of 99.6%.

3.3.3 Relative accuracy

Another major advantage of the proposed image-based surveying solution is the possibility of achieving a high relative accuracy for the distance between two points, since error sources that affect the global coordinate estimation are largely reduced by differencing. As mentioned in section 2.2, the features extracted from the collected images establish a geometric connection between subsequent images and the bundle adjustment refines the relative orientation and position of the camera poses. Therefore, the measurement of a distance between two object points in the same image group could reach mm-level accuracy, because systematic errors affecting GNSS positioning for instance have only insignificant effects on the relative accuracy. To assess the achievable relative accuracy, distances between two points in the same image group were measured. Figure 7 illustrates three reference distances (2.098 m, 1.410 m, 9.212 m) with different orientations on a building facade. These distances were measured in 42 image group datasets, where the ground truth was obtained by means of a high-precision total station.

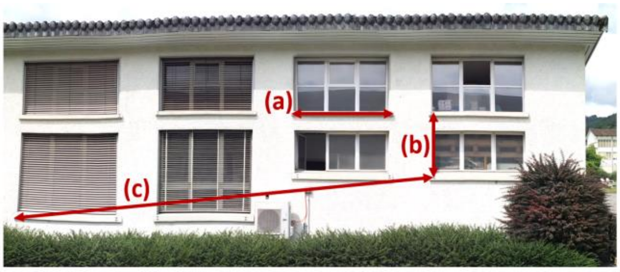

Figure 7 Defined reference distances on a building facade for evaluating the relative accuracy of the image-based surveying system.

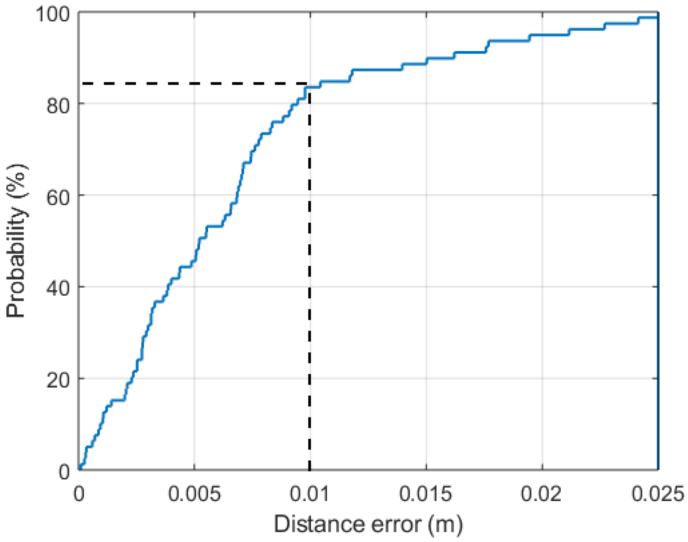

Figure 8 Error distribution of the distance measurements between two points in the same image group.

In terms of relative accuracy, Figure 8 shows the empirical cumulative distribution function of the error between the measured distance and its reference value. The results show that the error of a measured distance is smaller than 1 cm with a probability of approximately 85%. Based on this high relative accuracy, surveying-grade applications such as length measurements and areas can be performed efficiently by applying an easy-to-use workflow.

4. CONCLUSIONS

This paper presented an innovative image-based surveying approach that enables accurate remote point measurements by fusing GNSS and INS with terrestrial photogrammetry directly in the field. As a result, georeferenced measurements with centimeter-level accuracy become possible even at locations that are inaccessible with a conventional GNSS rover. Representative tests were carried out by considering various camera-to-object distances and trajectories varying in length and geometry to evaluate the accuracy and reliability of this novel sensor fusion platform. The results show that the combination of photogrammetry with a GNSS/INS system offers enormous potential in land-based surveying applications, where georeferenced coordinates are demanded within the shortest time. The main findings from the case studies are summarized as follows:

- The photogrammetric measurements are directly georeferenced in a global reference frame defined by GNSS without additional time-consuming post-processing steps or need of ground control points.
- Areas that were previously inaccessible for a GNSS rover can now be surveyed directly without any additional equipment.
- High-precision remote point measurements are possible with this image-based surveying approach, where the 2D and 1D RMS errors are 2.9 cm and 2.5 cm, respectively.

- The quality indicator (CQ) is a reliable measure of the position accuracy. The test results show that the 3D error is less than three times the CQ with a probability of 99.6%.
- Distance and area measurements within the same image group can be performed with a high accuracy. The analysis on the test case depicts that about 85% of the distance measurements exhibit an error smaller than 1 cm.

By bringing sensor fusion and computer vision together, significant improvements can be achieved in surveying applications, particularly in terms of productivity. The proposed technology of an innovative image-based surveying system allows an efficient workflow to measure remote points in a global reference system in the field. Capturing a whole scene within the shortest time and measuring obstructed points directly with a GNSS rover can be performed with high accuracy, productivity and flexibility.

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