New Measurement Methods for Structure Deformation and Objects Exact Dimension Determination

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Abstract. The current rapid development of technologies enables new procedures for deformation and the detecting of construction defects and their modelling and monitoring in BIM. New instruments were developed for fast and sufficiently accurate mapping like personal mobile laser scanners (PLS). In the world of photography, the size of camera sensors is bigger, and the photographs are sharper. The rapid development of computer performance enables automatic and complex calculations, which lead to large sets of detailed 3D data and a high degree of automation. This influences photogrammetry and its methods. The results are more detailed and more accurate. Deformation, defects and exact dimensions (metrology) of different structures or objects can be currently measured by digital close-range photogrammetry. Cracks and cavities are monitored for structure status detection. This is important for planning reconstruction and for financial reasons. For structures like cooling towers, chimneys, or bridges can be created on a 3D model with a high texture resolution for finding and monitoring cracks and cavities. Deformations or defects that were found must be in scale, and measurable for the calculation of the scope of repair work and its price. The generated 3D object model can then be used for further measurements, for the price estimation of renovation, and for the creation of a BIM, in which all processes can be modelled and watched. Deformation can be monitored over time by creating additional models after a defined period. Captured 3D models from different periods can be compared in software like CloudCompare to determine the progress of degradational changes. The trend of the aging of the structure can be traced, which will be helpful for the reasonable planning of reconstruction. Based on the rapid development and miniaturization of measuring devices, new, smaller, easier to use, and more perfect devices are constructed. This also applies to the new group of laser scanners constructed for basic measurement and structure modeling for BIM. Conventional laser scanners can be accurate, but they are relatively large and heavy, difficult to transport and measuring with them is relatively slow (stop and go type). If the project goal is the classic construction, documentation of the object, data transfer to BIM or basic documentation of objects, PLS is the ideal device. Thanks to the development of accurate IMU (inertial measurement unit) and SLAM (simultaneous localization and mapping) technologies, these devices are on the rise. The forthcoming article will inform about the methods of accurate close-range photogrammetry and mobile laser scanning and will show their advantages with specific examples.

1. Introduction
The detection of object deformation and their monitoring is a traditional area of geodetic methods. With the development of digital technologies and new devices equipped with sophisticated microelectronics, measurement is more accurate and easier [1]. There are different measurement methods for different results. Each measurement device has a specific purpose. The decision of selecting a measurement device depends on the accuracy, resolution, and type of the 3D model. Data
for the creation of the 3D model is mainly collected by a laser scanner or using close-range photogrammetry.

In the last year, the development of laser scanning has had a sharp increase. Personal mobile scanners were developed, and static scanners are faster, and automatic registration of laser scans are done in the field. This helps for adaptive application for different projects. The laser scanner can capture points with 3D coordinates by measuring angles and distances. The process of scanning is fast, with millions of points are captured in minutes. Clusters of these points are called point clouds. The point cloud is separated by the type of scanner.

1.1. Static laser scan
A static laser scanner is more accurate than the mobile laser scanner, but the time of measurement is also longer. The spatial accuracy of points is between 1 – 5mm, which depends on the producer. Further accuracy depends on the reflection of the scanned material. Shiny materials and glass are very complicated for scanning. Laser rays create ghost points from these materials. Ghost points cause problems with registration. Point clouds of the static laser scanner are joined at separate measured positions. This process is called registration. The mainly used methods of registration are target, visual or cloud-to--to-cloud registration [2, 3].

1.2. PLS - personal mobile laser scanner
PLSs are currently very rapidly evolving devices and their cost is considerable. PLS generally consist of a mobile unit, one or more lidars, sensors, cameras, an IMU, and GNSS equipment. It depends on the configuration that defines the use of the device. The ZEB-REVO device in various configurations is very popular. They are relatively cheap, light, portable and are mainly used for measuring interiors. The data is then an excellent basis for the spatial object component in BIM. The larger and more robust devices are, for example, the Leica Pegasus or Greenvalley, equipped with precise GNSS equipment and SLAM technology. The compromise between PLSs is BLK Go, which is developed from the static TLS system BLK360. The undeniable advantage of these devices is the speed of data acquisition and a fast, often fully automatic result in the form of a textured or non-textured point cloud. The disadvantage is the lower accuracy of the 3D points, which is usually 1-3 cm per 10 m, and the considerable noise in the data [4].

1.3. Photogrammetry
The use of close-range photogrammetry has increased enormously in the last decade. Thanks to rapidly evolving computer technology, fully automatic methods of creating 3D textured models have spread to all branches of science and technology. The technologies are variously named but create 3D models based on image correlation (SfM - (Structure from Motion, IMBR - Image-Based modelling and Rendering). The accuracy of ground photogrammetry has also been significantly increased due to subpixel interpolation and accurate automatic determination of the centers of the measuring marks. With a suitable configuration, the size of the marks, and a shorter distance, the accuracy of determining the center of the mark can be achieved up to 10 micrometers. This is, of course, sufficient for most deformation analyzes or for documenting structure load tests. Diversity is also found in types of 3D models. The main divide is the vector model and the mesh model. The mesh model consists of triangles joined together. The mesh model is mainly used for the visualisation of the true colour object or structure. The true colour is achieved by the texture, which is created by photos. The Vector model is created from point cloud blueprints or modelled from scratch. This model is mainly used for digital twins [5-7]. Measured data from laser scans and photogrammetry is very disk space consuming. Workstations must have large disk capacity, which also have high read and write values. The best working storage is an SSD disk which meets the conditions. The next requirement is good computer power given by CPU and GPU and enough RAM.
2. Methodology of deformation analysis

2.1. Laser scanning

By laser scanning, the comparison of two-point clouds from the same object captured at different times is mainly used. CloudCompare software is very often used, which can calculate the distance of both clouds. It is necessary to realize, however, the direction of displacement or deformation; the point cloud distance is calculated as the distance between clouds at normals. However, this does not always accurately describe the displacements and deformations of the object (the deformation doesn’t must be in the direction of normals). For this reason, in many cases, it is necessary to use the method of local cloud shift using Model-to-Model Cloud Comparison (M3C2) technology. For certain projects, it is necessary to scan an object with precisely defined targets (usually spherical targets are used, the center of which can be analytically precisely determined based on detailed points on the surface of the target). For PLS devices, determining accuracy is more difficult. If the device moves in free space outside the building, GNSS technology and control points can be used, which can be measured geodetically or using GNSS RTK. Inside the building, we rely only on the classical geodetic measurements of control points, usually defined by flat targets. However, the identification of the centers of the targets is not very accurate from the point cloud. If the PLS does not have a camera, the exact search for the target center is not very accurate. Therefore, the accuracy of the analysis of point clouds, taken in a certain time interval, is not perfect to detect the object deformation in time [3].

2.2. Close-range photogrammetry

Photogrammetry has gone through several development stages, from analogue photogrammetry, through analytical to digital. Depending on the development of computer technology, the digital technology won in the mid-1990s. After the year 2000, the performance of ordinary computers was already sufficient for new technologies of automated photogrammetry (SfM, IBMR). The abbreviations express that the technological principle is the movement of the camera around the object and image processing, which creates a 3D model of the object. Similarly, these technologies can be used for aviation methods, especially for mapping or documentation from drones. The result is always a point cloud, just like with laser scanning. The process of creating a dense point cloud from images using the close range photogrammetry method can be divided into three phases: data collection, extraction of a sparse point cloud (calculation of internal and external camera orientations) and subsequent extraction of a dense point cloud, computing of mesh and orthophoto. The main advantage of close photogrammetry is that only a digital camera and software based on digital image correlation are needed for this work (Agisoft, Photoscan - Metashape, Zephyr 3D, pix4D, 123catch, etc.) [5, 6]. The photogrammetry is simpler, as very detailed images of the object are always available. Identification of the centers of marks or targets is good in the images, when either classic circular centric (reflect) marks or coded targets are used.

The result is:
- a relatively small number of artificially signalised (using reflected self-adhesive marks, for example), but very precisely spatially determined points,
- a dense cloud, as by measurement with a laser scanner, which can be precisely referenced by control points in a reference frame; the deformation can be determined from the point clouds differences

Both laser scanning and close-range photogrammetry are used as a basic spatial documentation for BIM [8, 9].

3. Case study

3.1. Bridge

The 3D model of a bridge was created for detection of cavities and cracks and modelling in BIM. A mesh model with high resolution texture was as the result. Output format can be obj + mtl + image
texture or fbx + image texture. The processed mesh model has a right scale and geometry, so it can be used for the modelling of a vector model in BIM. The mesh model can be used for visual detection of cracks and cavities. For capturing the data of concrete structure, geodetical targets are needed (Figure 1). It is mainly that the concrete structure does not have high contrast and significant texture. Targets are used for joining data from photogrammetry and laser scanning. They must be spread across all objects to get a good joining of all measured data. The size of the target is essential, they must be considered; targets must be detectible with photo and laser scans.

![Figure 1. Using of targets on concrete parts](image)

In this project, a terrestrial laser scanner (TLS), aerial (drone), and terrestrial photogrammetry were used. Joining of both technologies has important advantages. TLS adds a scale to the model; photogrammetry can be often dimensionless (or the scale is not precise), because only picture coordinates are used (pixel lines). The model was processed in Metashape software, which can work newly with both laser and image data. Mobile laser scanners cannot be used because data from PLS has lower precision in comparison with TLS and photogrammetry. Metashape photogrammetric software cannot handle work with this type of data. Laser scanned data must be registered, but each position must be saved in a single file in the format *.e57. Metashape software deals with laser scanner data as with 360-degree panorama photos. Taking a photo must be considered for good target visibility and their easy detection. The scanning resolution depends on the type of structure and the distance between the laser scanner and the scanned object. High resolution scanning is elected on the area where the object is far away from the laser scanner. The length of distance affects the coordinates accuracy in the point cloud. Concrete structures are very good to reflect laser rays. A double reflected point, for example, caused by glass material, does not degrade the final point cloud. Today, areal photogrammetry can be made using a drone with a high resolution RGB sensor. Selection of the drone depends on the resolution of the final texture and the possibility of the scanned object. Small drones can be a benefit in an area with low space for flying. Bigger drones can be equipped with a professional camera, but they can be used in the open area only. While capturing photos of the concrete structure, a situation can appear where the camera or focal length must be changed. For photogrammetry, it is recommended to not change the focal length. In an area with small space, it is better to use shorter focal lengths, for example, 18mm. The final resolution of the texture depends on the scale of the cracks and abnormalities; they must be visible in the created model. If it is needed to see cracks of 1 mm size, the GSD must be twice as low as a typical crack width. Usually, a captured
single laser scan can be joined with software given by equipment dealers, but nowadays there are a large number of universal software for point cloud processing. Registration is done by the method Cloud2cloud using the correlation of highly overlapped scans or based on targets. The accuracy of registration depends on the accuracy of the laser scanner, the detection of targets, and finally, on the given coordinates, if the targets are used as a control point. The creation of the final joined point cloud or mesh model from both laser scans and photo data can be done in photogrammetrical software like Agisoft, Metashape, or Reality Capture. Both software can process the registered laser scan and photos into a mesh model. It is better that all photos are captured with the same sensor and same focal length. Software allows alignment photos with different parameters, but for a bigger photo set it is better to separate photos with different parameters into special directories. After aligning of the photoset with the same focal length, this group can be joined in one component. Each group must consist of at least three markers - tie points, which allow the transformation of all groups to one component. Markers must be defined on at least five photos to fix the stable coordinates of each marker in 3D (Table 1).

| Drone                      | Mega pixels | Focal length [mm] | GSD 5m [mm] | GSD 10m [mm] | GSD 15m [mm] | GSD 20m [mm] |
|----------------------------|-------------|-------------------|-------------|--------------|--------------|--------------|
| DJI Phantom 4 PRO          | 20          | 24                | 1,1         | 2,4          | 3,5          | 4,7          |
| DJI Mavic 2 Pro            | 20          | 24                | 1,1         | 2,4          | 3,5          | 4,7          |
| DJI Mavic Mini             | 12          | 24                | 1,8         | 3,6          | 5,4          | 7            |
| DJI M600+SONY A7RIII       | 45          | 18                | 1,3         | 2,6          | 3,8          | 5,1          |
| DJI M600+SONY A7RIII       | 45          | 24                | 1,0         | 1,9          | 2,9          | 3,8          |
| DJI M600+SONY A7RIII       | 45          | 35                | 0,6         | 1,3          | 1,9          | 2,6          |
| DJI M600+ SONY A7RIII      | 45          | 50                | 0,5         | 0,9          | 1,4          | 1,8          |

Figure 2. Original photo of concrete construction part and digitized cracks

The process with laser scans is the same except one can consider that laser scans are already registered, so the alignment or joining of laser scans is used to view all data together only. When all important photos are in one component, laser scans are added in two markers. The next step is to compute the mesh model from the depth map. The creation mesh model based on the depth map is better and faster than the compute point cloud and the next generate mesh from the point cloud. The final step is the texturizing of the 3D model; this technology is called baking texture on the created mesh model. Software generates U, V maps to texture based on the mesh model, count, and size of texture. After the creation of UV, the map starts baking texture, which caused a good and stable
texture on the 3D model. This model is perfect for visualising and can be transferred into VR (virtual reality), for example, for a better and modern analysis of the object. For now, the search of any cracks and cavities, if it is done visually is not a tool for automatic defect detection in the model. This is a challenge for further research (Figure 2, 3).

![Figure 3. Partial damage of a concrete part (left), cavity detection (right)](image)

3.2. Close-range photogrammetry for metrology

The principle of close-range photogrammetry is successfully used today in digital times as well as was as in the past (analogue photogrammetry and time base technology, e.g. in bridge load tests). Here, in this case project, the CRP was used for metrology - for precise measurement of the dimensions of the engineering element. This was a giant metal casting for a hydraulic press. This metal casting has 80 tons with a dimension of 10 x 2 x 3 m. The Linearis photogrammetric system was used here only in the older and basic version (max. 500 images and an accuracy of approx. 0.1 mm) with coded targets and signalized object points. Images are oriented automatically based on the coded targets. The scale is given by two standards, which are inserted when measuring on the object (Figure 4).

![Figure 4. Measuring of metal casting](image)

The result is processed in the form of a bundle adjustment for all signalized object points. In this case, it is about 1500 points which determines the metal cast; the most important detail was to determine the perpendicularity of the bearing holes with a diameter of about one meter. The result was an independent verification of a more accurate method that uses not only coded targets and signal
points, but also structured light. This technology has a theoretical accuracy of 0.01mm and was therefore used as a reference and was more accurate.

3.3. **PLS and new miniaturized laser scanners for BIM**

In 2008, CSIRO (Commonwealth Scientific and Industrial Research Organization) developed a robust SLAM algorithm that focuses primarily on accurate 3D measurements and mapping rather than spatial navigation. SLAM was designed for devices that move through space. Systems based on SLAM technology work well when used in motion. It is also used in built-up areas, where SLAM technology helps construction professionals create fast and sufficiently accurate 3D models, created in a minimum of time (Figure 5). It is used, for example, in the following activities:

- rapid weekly monitoring of progress on construction sites,
- real-time survey of residential, commercial, and industrial facilities,
- comprehensive survey of existing buildings to be renovated, rebuilt, or extended,
- The basis for the creation of BIM.

![Image of ZEB-REVO Go, Greenvalley backpack, and Leica Pegasus backpack](image)

**Figure 5.** PLS BLK go a BLK360, ZEB.REVO Go, Greenvalley backpack and Leica Pegasus backpack

3.3.1. **ZEB-REVO Go.** ZEB-REVO Go is the simplest device of this type. It excels in ease of operation and small dimensions. However, he does not have a camera; there are other types of cameras, but it is not a 360 panoramic camera, as the device is hand-carried. The accuracy of the measurements was verified and analyzed by our own measurements in the basement of the Faculty of Civil Engineering of the Czech Technical University, where large targets were placed in the corridors (ZEB-Revo Go has a relatively low density of measured points and its accuracy is low compared to static laser scanners: it reaches an accuracy 1-3 cm on ten metres in the measured position of the point depending on the situation and type of object or material). The checkerboard-shaped targets measuring 60 x 60 cm were first precisely and geodetically measured using the Trimble-Zeiss total station. A total of 8 targets with a standard deviation of 1.1 cm were measured within the polygon. From the differences in the coordinates of the target centers, subtracted from the point cloud, and from the calculated coordinates of the target centers based on the total station measurement, the point standard deviation of the ZEB-Revo handheld personal scanner was calculated. The measurement of the total station is logically more accurate (with an assumed standard deviation in the order of mm) and was considered as a reference.

The figure shows the data measured by the ZEB-Revo Go scanner in the GeoSLAM HUB software, which is used to process the measurements, export data, and visualize them (Figure 6).
Figure 6. View of the point cloud (left) with PLS trajectory, the target on a tripod, and the diagram of the measured area (right).

The target centers were selected from the point cloud manually (as the estimated target center), see Figure. The accuracy wasn’t high for the uncertain selection of the target center due to the low density of point clouds. The centers of the targets were also measured geodetically by the Trimble total station. From this procedure, we get a set of identical points. Subsequently, the spatial transformation in the 3dTrans program was used (software for similarity or affine transformation in 3D, CTU FCE software). 8 points were used for the transformation, other points were used for control - using the calculated transformation key, these points were transformed from the coordinates of the point cloud into the local geodetic system, and their coordinates were compared with the geodetically determined ones. The deviations were within 1-3 cm, which corresponds exactly to the accuracy declared by the manufacturer. Other points were selected experimentally, the results were similar. After calculating the transformation, a standard deviation of 0.015 m was obtained at 8 transformed points. This accuracy is more than sufficient for the assumed usage in this work.

3.3.2. BLK2GO. BLK 2 GO is based on TLS BLK360; the IMU was added and new software was created. In this case, the project comparing of the PLS BLK2Go and TLS BLK360 for mapping of a building interior was shown. The interior of a large building was scanned with both devices and differences were sought both between the devices and differences in the project and construction documentation. All scanned parts were filtered to remove remote points and noise reduction was performed. A higher relative decrease in the number of dots can be observed for the BLK2GO scanner. This indicates poorer scanner accuracy. The accuracy achieved by the BLK2GO system was evaluated in the office room. The cloud created by the BLK360 scanner served as a reference model. Point clouds were compared in CloudCompare software. The achieved accuracy was estimated from the histogram. The mean error in determining the position of a point from the BLK2GO system can be around 1 cm. Relatively numerous deviations can be observed from the histogram, even beyond the 2 cm limit. A similar phenomenon is observed in practically all examined point clouds. The accuracy of approx. 1 cm is sufficient scanning accuracy for creating models of buildings that are of regular shape. However, the accuracy is insufficient to capture fine details in the model. The following figure shows the details of the door frame. The cloud taken by BLK2GO is shown in the upper half of the image. At the bottom is a cut-out from a cloud taken by BLK360.

3.3.3. Comparison of the point cloud with existing documentation. A horizontal section was made of the diluted point cloud, which was transferred to the existing drawing documentation. The figures show the discrepancy of the existing drawing documentation with the point cloud (blue colour). The displacements occur several times a decimetre, for example, the door opening at the bottom left (Figure 7).
Figure 7. Optical comparison of cut-outs; left G2GO, right BLK360. The figure above clearly shows the effect of data noise caused by scanner movement and IMU inaccuracies.

Figure 8. Color differentiation of drawing documentation with data from laser scanning, right: displacement of masonry building partitions

In the following figure, it is possible to observe relatively significant shifts in building masonry partitions (Figure 8).

3.3.4. Comparison of room parameters (dimensions)
The drawing documentation was created from the point cloud cross-section, which was then compared with the existing drawing documentation. The following table compares the created BLK360 documentation. The acreage and dimensions of the rooms were compared. The maximum difference in acreage reaches 2 m² and the maximum difference in measured distance reaches 0.5 m (Table 2).

| Room Nr. | acreage [m²] | Comparing of distances [mm] | Difference [mm] |
|----------|--------------|-----------------------------|-----------------|
| 190      | Project: 17.99, Measured: 17.44, Difference: 0.55 | Project: 5350, Measured: 5394, Difference: 36, Project: 3360, Measured: 3258, Difference: -102 | -44 |
| 191      | Project: 16.14, Measured: 16.22, Difference: -0.08 | Project: 5010, Measured: 5077, Difference: 67, Project: 3020, Measured: 3024, Difference: -4 | -67 |
| 192      | Project: 16.74, Measured: 16.36, Difference: 0.38 | Project: 5360, Measured: 5389, Difference: 29, Project: 3120, Measured: 3015, Difference: -105 | -29 |
| 193      | Project: 16.17, Measured: 17.51, Difference: -1.34 | Project: 5038, Measured: 5122, Difference: 64, Project: 3020, Measured: 3256, Difference: -236 | -84 |
| 195      | Project: 34.63, Measured: 36.60, Difference: -1.97 | Project: 5380, Measured: 5366, Difference: 14, Project: 6350, Measured: 6754, Difference: 404 | 14 |
| 196 + 196a | Project: 17.80, Measured: 18.26, Difference: -0.46 | Project: 2760, Measured: 2753, Difference: 7, Project: 6405, Measured: 6725, Difference: -320 | 7 |
| 196p     | Project: 10.29, Measured: 11.71, Difference: -1.42 | Project: 2760, Measured: 2764, Difference: -4, Project: 3730, Measured: 4239, Difference: -509 | -4 |
| SCH4     | Project: 15.56, Measured: 15.45, Difference: 0.11 | Project: 2430, Measured: 2418, Difference: 12, Project: 5945, Measured: 5959, Difference: -14 | 12 |
4. Results and discussions
This example shows the inaccuracy of the existing construction documentation, which can be very well defined based on laser data. The BLK2GO mobile handheld laser scanner acquires a considerable amount of data. At the same time, their accuracy is not completely adequate for their amount, unlike, for example, the ZEB-REVO mobile laser scanner. Created model is perfect for visualising and can be transferred into VR (virtual reality), for example, for a better and modern analysis of the object [10]. In this time, the search of any cracks and cavities is done visually; is not a tool for an automatic defect detection in the model. This is a challenge for further research.

5. Conclusions
This article discusses new possibilities for measuring deformations and shifts. Modern laser scanning procedures were used, both using small laser scanners and especially PLS. These devices are increasingly becoming common practice because their accuracy and usability are sufficient for most mapping work. It is possible to determine the differences, for example, between the construction documentation and reality, as well as the differences between the design and execution of the construction, or the new space modification. This goes very quickly and accurately in the exterior and interior. The results can be very well used for visualization and analysis in VR.

However, the measurement of small deformations depends on their real size. Millimeter deformation or shifts cannot be detected by conventional laser scanners. Modern automatic digital close-range photogrammetry proves to be a suitable method, whether with coded targets or only with classical targets. Their centers can be determined analytically with subpixel accuracy, and the accuracy of deformation or displacement measurements of up to about 10 micrometers can be achieved.

In conclusion, it can be said that both laser scanning and photogrammetry can be used to acquire a point cloud, which are both now the basis for modelling objects in 3D. It depends on the details and accuracy and size of the documented object.

Acknowledgment(s)
This contribution was sponsored with the grant CTU SGS Nr. SGS21/054/OHK1/1T/11.

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