IOP Conference Series: Earth and Environmental Science

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To cite this article: Gergana Antova 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **221** 012082

IOP Conf. Series: Earth and Environmental Science 221 (2019) 012082 doi:10.1088/1755-1315/221/1/012082

Application of Areal Change Detection Methods Using Point Clouds Data

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Abstract. Surveying techniques such as Terrestrial Laser Scanner have recently been used to measure surface changes via 3D point cloud (PC) comparison. Since there are no signalized points when using laser scanners and no identical points between two epochs, judging an object change detection can only be based on areal methods. A surface based analysis is able to detect changes that are unknown and spread along the whole surface. Existing methods for point cloud comparison and the source of uncertainties are reviewed in the first part of the paper. Current comparison methods are based on a closest point distance or require at least one of the point cloud to be meshed. Better results can be achieved with using Least Square Adjustment of polynomial surfaces (planes and quadric height functions) applied on point cloud data. Examples for change detection based on measurements obtained from terrestrial laser scanning for a double-arc object are given. Two areal methods for comparing two point clouds are used and the obtained results are analyzed.

1. Introduction

The result of terrestrial laser scanning (TLS) point clouds are modelled for various purposes: a preview of the scanned objects from different perspectives, generate a digital model of the terrain and buildings for the purpose of planning, presentation of constructional elements of buildings in information systems such as Building Information Model [1] as well as the tasks for reconstruction of the already built objects to be compared with their project plans. These are just some examples of application. Each of these examples is a key task in at least one discipline. The tasks of modeling and comparing are applied to objects of different sizes and have different requirements for accuracy. This focus is particularly important in tasks associated with modeling of point clouds to determine the deformations and change detection tasks. Lidar for various surveying applications such as deformation monitoring and damage detection has increased rapidly. Terrestrial Lidar is used in civil engineering applications in structural monitoring [2] of dams, tunnels, road modelling, bridges and towers, evaluating deformations and/or geometric changes of special objects, drift detection, natural hazards and structural analyses in cultural heritage. In Engineering Geodesy TLS is used to register changes in the geometry of the object. Because it is not possible to measure the same points in different epochs, this leads to the need for development of methods for point cloud comparison. Due to the literature the existing methods could be divided to 3 types shown in Figure 1.

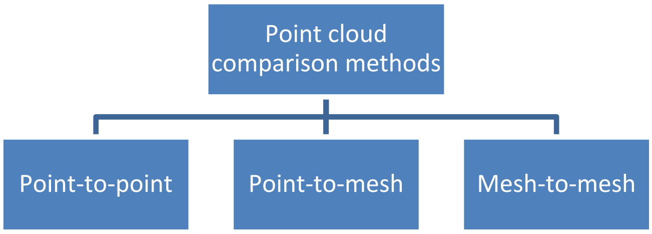

Figure 1. Point cloud comparison methods

- Direct cloud-to-cloud comparison with closest point technique
  - 7 parameter 3D transformation
  - Iterative Closest Point algorithm
  - Regular grid points
- Cloud-to-mesh distance or cloud-to-model distance
  Improvements of point-to point can be obtained by a local model of the reference surface by using appropriate approximating surface [3]:
  - Using plane approximation
  - Normal vector estimation
  - Base line method
- Mesh-to-mesh (model-to-model)
  - Digital Surface Model (DSM)- cannot cope with overhanging parts (cliffs and bank failures, large blocks,)
  - Volume calculation,
  - Regular grid points,
  - Sections.

This paper is organized as follows. In Section 2 existing methods for distance measurements between two point clouds and the source of uncertainties are reviewed. Section 3 present the experiment description and the framework of proposed methodology with the experimental results and their analysis. Finally, Section 5 summarizes the main points of the study and looks into future work.

2. Distance calculation between 2 point clouds

This section describes what kind of distances could be measured between 2 point clouds and how they could be calculated. Two kinds of distances are described below:

- Distances between two point clouds (cloud-cloud distances),
- Distances between point cloud and surface (cloud-mesh distances).

2.1. Cloud-To-Cloud Distances

It's generally not so easy to get a clean and proper global model of a surface. Therefore, the idea of cloud to cloud distance is proposed which is the classical way to detect changes. The principle of nearest neighbour distance is used to compute distances between two points: for each point in the compared cloud, the nearest point in the reference cloud is searched and their Euclidean distance is computed [3, 4].

Another immediate way, getting a better approximation of the true distance to the reference surface, is to get a local surface model. When the nearest point in the reference cloud is determined, the idea is first to locally model the surface of the reference cloud by fitting a mathematical primitive on the 'nearest' point and several of its neighbours, see Figure 2. The distance to this local model is finally reported. Common ways to locally model a surface are by triangles, compare Figure 9, by planes or by otherwise smooth patches. The effectiveness of this method is statistically more or less dependent on the cloud sampling and on how appropriate the local surface approximation is.

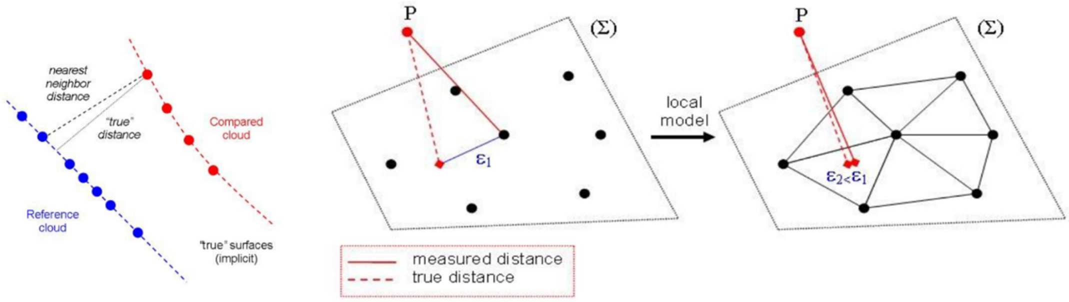

Figure 2. Global (left) and local (right) surface model for cloud-to-cloud distances

If the reference point cloud is with sufficient density, the calculated distance is acceptable. But if the reference cloud is not of sufficient density, distance calculated with the closest neighbour is not sufficiently precise. It is therefore necessary to obtain a better model of the surface. The idea is, when you find the nearest point in the cloud reference to a local part of the reference model surface by fitting a mathematical model of the "nearest" point and several of its neighbours. So the distance from any point of comparison cloud to its nearest point in the reference cloud is replaced with the distance to its local model. Statistically it is more accurate and less dependent on the density of the cloud. Locally it can give strange results, but globally are much better.

The mathematical model can be selected as: best fitting plane in Least Square Adjustment (LSA) or 2.5D Delaunay Triangulation or second order function (the latter is more precise but longer for the calculation). The way in which the neighbours are selected around every "nearest" point on the reference cloud is or by setting a specific number of neighbours or by setting the radius of the sphere. When you compare two cloud directly (especially without model) it is necessary to comply with several requirements:

- The reference to the reference cloud is wider than the clouds being compared (to avoid practical long distances at the borders). More generally, the reference cloud always overlap comparison.
- You should always operate with the highest possible density for the reference cloud (because it will directly change the accuracy of results).
- If the compared cloud is very noisy, it is better to use the most appropriate model of plane in LSA (which is more resistant to noise). On the contrary, if the reference cloud is pure, but with large curvature, it is more appropriate to use a second order function.
- It gets more complicated as the point clouds are noisy and “distance” takes other meaning [5].

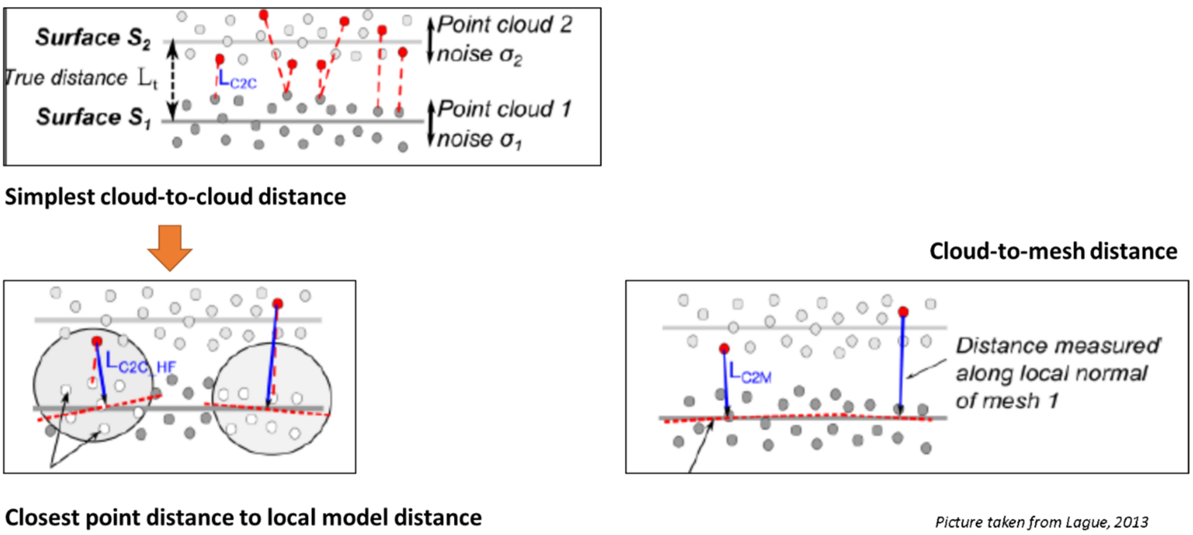

Figure 3. Distance measurements between point clouds with noise

3. Case study and measuring setup

3.1. Description of the object

Cankov Kamak dam is situated in Rodopi Mountain in the southern part of Bulgaria. The structure, built in the 2014 is a concrete double arch dam with 130 m maximum high and 468 m length on the crest.

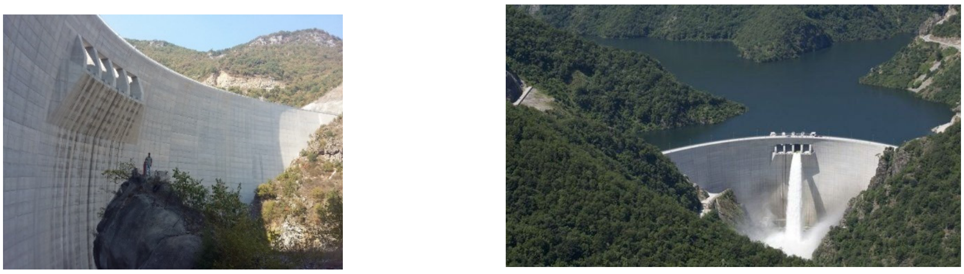

Figure 4. Cankov Kamak dam, frontal and air view of the dam

3.2. Laser scanning measurements -Acquisition of test data for accurate change detection

For high precision survey scanners, the total error budget on change detection is dominated by the point clouds registration error and the surface roughness. Laser scan measurements from one fix scan position is made in order to minimalize the registration error. The instrument LeicaNovaTM50 data acquisition with precision (also known as scanner noise) of the measurement at 350 m was measured at 1.5mm on this instrument (given as one standard deviation), while accuracy was of the order of 2 mm up to 500 m. Measurements in both cycles were carried out under the following conditions in order to reduce the impact of the error in the registration of the clouds.

Plan of work:

- the introduction of corrections for atmospheric conditions (ppm) temperature and altitude;
- orientation;
- 62 Hertz frequency scanning and density 20 cm along the two axes;
- measurement of 150 single points on the wall with high precision.

The instrument was placed on the supporting network for the monitoring of the deformations. The orientation is carried out with an automatic grip to the 3 points of the network. In Epoch 0 the measurements were carried out at water level 671 m, air temperature 28 degrees. In Epoch 1 the measurements were carried out at water level 680 m, air temperature 10 degrees. Two million points are measured.

Figure 5. Measuring setup- acquisition of laser scan data for accurate change detection

4. Methodology

Taking into account the specific nature of the algorithm used in the software Autodesk Civil3D, it is necessary to rotate the model, as it is shown in Figure 6, so that the triangles are built in ZY plane and difference in X- direction (near to the dam normal) represents the deformation. As a result, differences in 15000 point with 1 m density are interpolated.

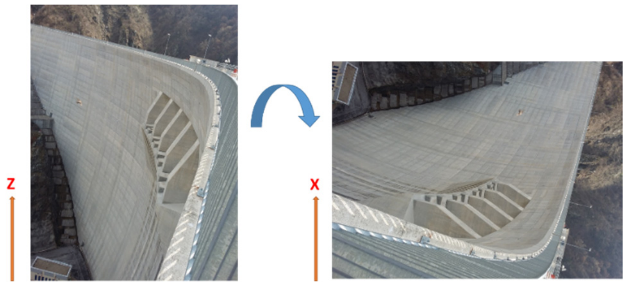

Figure 6. Structural Coordinate System Establishment and Coordinate Transformation

First direct mesh-to-mesh comparison is made in direction X in Autodesk Civil3D. The results are given in Figure 7. It can be seen that measured deformation in central upper part of the dam is with larger value than other parts and bottom of the dam, which corresponds with the expectation of movements and is confirmed with the results of daily monitoring of the dam.

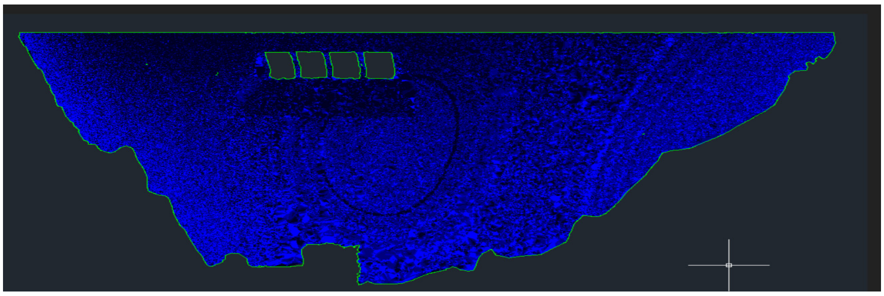

Figure 7. Mesh-to-mesh comparison in direction X in Autodesk Civil3D

4.1. Regular network comparison

Direct comparison of single points without using brands is made, where the points are located on a regular network created by the method of Delaunay-Triangulation [6]. Then for each point a new value (y') can be interpolated. The difference between the two corresponding (y ') coordinates represent the distance between two point clouds (Figure 8).

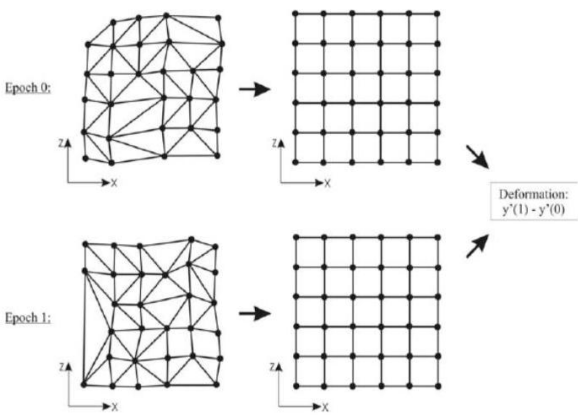

Figure 8. Raw point clouds with an irregular model (left) and the interpolated regular grid (right) identical for every point cloud epoch. The difference in y- direction represents the deformation [7].

4.2. Sections

More precise representation of the deformation results made by using sections of the deformation surface. Sections in horizontal and vertical direction are made and presented in Figure 9 and Figure 10. The trend function is calculated to reduce the noise of point clouds data. From the sections it could be seen clearly the absolute value and the trend of the differences between two epochs measurements. Other work with application of sections of mesh model is described in [8].

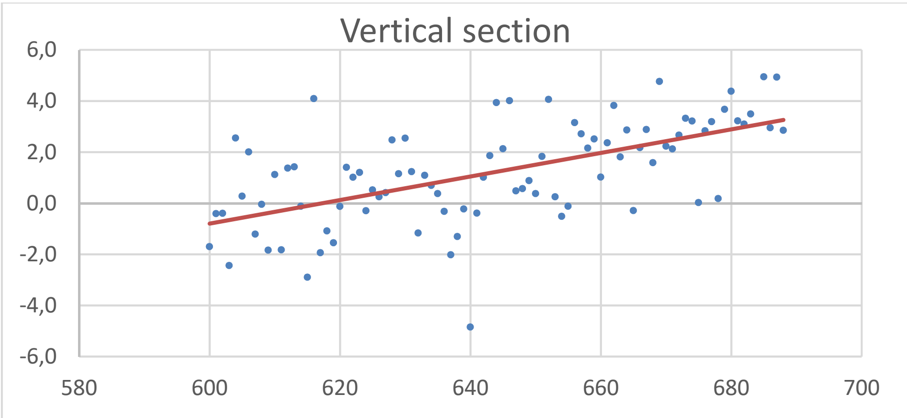

Figure 9. Vertical axis describes the differences (units in millimetres) between Epoch 0 and Epoch 1, the horizontal axis shows elevation of the dam (meter). Trendline is calculated as linear function

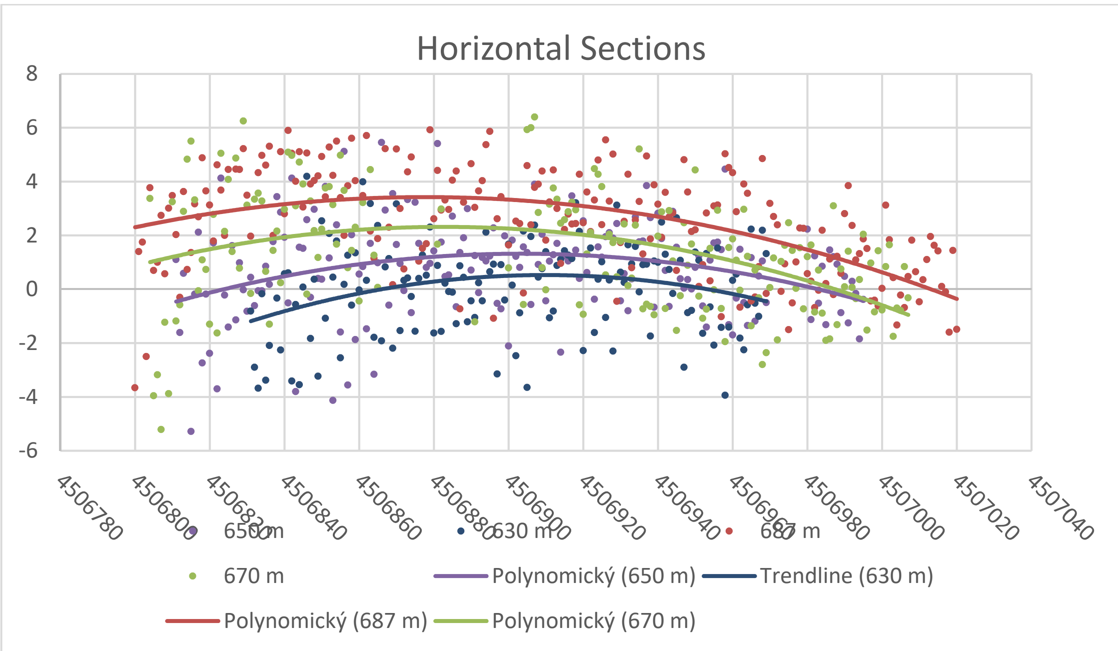

Figure 10. Vertical axis describes the differences (units in millimetres) between Epoch 0 and Epoch 1, the horizontal axis shows coordinates along the dam crest (meter)

Trendline Equation of second order function and R^2 value

H=685 m	$y = -0.0002x^2 + 1927.5x - 4E+09$	$R^2 = 0.0941$
H=670 m	y = -0.0002x2 + 1904.9x – 4E+09	$R^2 = 0.1573$
H=650 m	$y = -0.0001x^2 + 1308.6x - 3E+09$	$R^2 = 0.2611$
H=630 m	$y = -0.0003x^2 + 2500x - 6E+09$	$R^2 = 0.0672$

It could be seen that left part of the dam that is in shadow all the year is moving differently than the right site where it is sunny.

4.3. Validation of results
Statistical analysis of differences is made and the results shows normal distribution of differences with standard deviation of 1.3mm. Results are confirmed by daily monitoring measurements.

5. Conclusions
In this paper a mesh-to-mesh method has been presented that identifies deformations in objects from repeated laser scanning data. This method was demonstrated on a dam structure in Bulgaria. The dam was scanned in different conditions- low and high water level and respectively high and low air temperature which caused recognizable displacements.

The change of the surface is calculated by the distance between the regular grid points and 3D meshed surfaces. This approach works well on flat surfaces. Creating a meshed surface, however, is complicated for point clouds with significant roughness or missing data. This usually requires the withdrawal of time for manual verification. As for the DSM of differences, on missing data interpolation therefore introduces uncertainties that are difficult to quantify. The mesh also smooths out some details that may be important for the assessment of local properties of roughness.

Future work is needed for testing different methods for regular grid modelling [9] and determination of the sources of uncertainty in the comparison of point clouds data. Three main sources can be identified:

- Uncertainty of the position of the clouds of points: latest generation pulsed scanners offer the precision of the measured distance to 1.4 mm (accuracy). These characteristics are increased with the distance and slope angle.
- Uncertainty in the registration of clouds of points [10]: with the exception of the rare case when the scanner changes right in the same position like in this research, the coordinate systems of both the cloud have a systematic error, which is a complex function of the method used for registration of both clouds. The accuracy and precision of the instrument play an essential role in the final registration error.
- The errors associated with the roughness of the surface: even if the surface does not change, it will be systematically measured wrong small differences. Then properly defined confidence interval must reject the difference as statistically meaningless. The roughness will also affect the calculation of the mesh which can potentially lead to low- or overestimation of the distance between the two clouds. The contribution of effects of roughness for the sum of errors is the least constrained by all.

Acknowledgment(s)
Authors wishing to acknowledge Bulgarian office of METRISYS Ltd. for technical support and assistance of technical staff. Special thanks to the management company NEK EAD “Dams and Cascades” for the access to the dam.

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