Trends in detecting changes from repeated laser scanning data

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***Abstract*—Change detection is an important application of laser scanning data. It is also a challenging application as errors that are inevitably present when determining the geometric state of a scene of interest in a certain epoch will somehow add up when comparing the geometric state between epochs. As a consequence it is often difficult to distinguish real changes from differences caused by measurement and/or processing errors. On top of that, data volumes are rapidly increasing. Therefore successful change detection methods should not only be robust against errors but also computational efficient. In this paper a not necessarily complete overview of recent methodology is given that is presented in connection with the applications considered by the original authors.**

Laser scanning; change detection; deformation analysis; review; data quality; point clouds

I. INTRODUCTION

Since laser scanning matured as a surveying methodology, people have tried to identify changes in a scene or on an objects surface from repeated LIDAR surveys. Actually change detection, deformation analysis and structural monitoring is different terminology for strongly related topics. For laser scanning all these topics have in common that all compare point clouds of the same scene or object, but acquired at different epochs. From these comparison conclusions are drawn on the local geometric state of the object or scene.

Before point clouds are ready to compare, the input point clouds have somehow been acquired and aligned. Data from each epoch may have a different error budget, in most cases the quality of point cloud data is even strongly varying with the location within the point cloud [1]. On top of that additional uncertainty is introduced by the alignment procedure, a process also referred to as registration. This setting for change detection and related methods for point cloud comparison exists for several years now and different methodology exists for dealing with challenges like data blunders, uncertainty variations, occlusions, varying point densities and detecting changes of individual objects in a complex scene.

In this paper a review is made of both established methodology and recent methods triggered by two recent developments that add more challenges to the topic. First, equipment for point cloud acquisition is quickly spreading: laser mobile mapping systems, Kinect range cameras and smart phones (using photogrammetry) are three relatively new sensor systems for acquiring points clouds. As a consequence it becomes feasible to combine and consecutively compare point clouds acquired from completely different sensors. The second challenge is the recent increase in data volume. Notably laser mobile mapping systems sample complete cities at a rate and point density that makes it very difficult to extract the potential of information contained in the data.

There are also two developments that are directly triggered by the maturing of the laser scanning technology. First, more methods become available to characterize the quality of acquired data. The availability of such methods complicates data acquisition and processing, as these more sophisticated method should be integrated in the workflow. But clearly the error bounds of the results can be reduced together with reducing the error bounds of the input data. Another development is that laser scanning becomes more and more known as a surveying technique to a wider audience. The consequence of this is that laser scanning is now often only part of a bigger project. For example, the result of a laser scanning survey could be used to set boundary conditions for a numerical simulation.

The different methodologies and developments are illustrated on applications like change detection in tunnels, laser archive updating and street inventory monitoring.

II. METHOD BREAKDOWN

In Chapter 7 of [2] I already presented a first breakdown of methodology aiming at change detection and deformation analysis. This division in approaches is first shortly recalled. Then for each type of approach new methodology, if present and identified, is discussed. Finally it is considered if totally new approaches exist or are needed.

A. Preprocessing: registration

In the following it is assumed, if not stated differently, that point cloud data representing the same location is available for at least two epochs. It is also assumed that point clouds are represented in the same local or global coordinate system. In practice this means that already some preprocessing took place, often dependent on the method of acquisition.

Point clouds acquired by a mobile platform, such as an airplane or a car are typically directly georeferenced which means that the position of the platform in a global coordinate system is obtained by a Global Navigation Satellite System (GNSS) and its orientation by an Inertial Measurement Unit (IMU). The global coordinates of a point whose distance to the platform is measured by laser ranging is then obtained by combining all measurements together with the orientation of the laser at acquisition time. In contrast, panoramic scans obtained from a static viewpoint are typically concatenated to form a larger point cloud by 3D matching. Initially such point clouds are in a local coordinate system. If necessary, conversion to a global coordinate system can be made by incorporating known global coordinates of targets visible in the cloud. Specific methods are discussed in Chapter 3 of [2].

It is important to note that the processes of registration and/or georeferencing add to the error budget in a particular way. When concatenating scans, but also when applying a strip adjustment, i.e. the fine matching of points from different flight lines in airborne laser scanning, most often use is made of a rigid body transformation. Such transformation rotates and translates one point cloud in such a way that it optimally matches another point cloud. When comparing registered data from different epochs this process notably results in systematic shifts resembling changes at locations in the matched point cloud away from where the matches were made. In georeferencing, errors in the positioning and orientation directly propagate in local varying errors in the resulting point clouds. Both georeferencing and registration errors are often at the millimeter to centimeter level, and are therefore often higher than the error in the laser range, and are as a consequence easily misunderstood as change.

B. *Overview of approaches*

In [2] I make the following distinction between change detection and deformation analysis. Change detection looks for a binary answer, is a situation changed or not: is the tree still there or was it removed. Deformation analysis looks for a quantified change: How much did the tree grow in three years? Essential for choosing a method to answer either of the two different questions is the expected signal to noise ratio. If changes are large and obvious, a simple and efficient method should be used. Only start using more involved methods when this is required by the application. If in doubt, start easy, for example by using only part of the available points, and use more advanced methods only if the initial results indicate so.

C. *Change detection*

As stated above, the purpose of change detection is to determine if the geometric state of a scene has changed. One particular challenge connected to this topic is to distinguish between changes and occlusions. Laser ranging always determines the distance from the laser device to the scene. If the line of sight of the laser device to a part of the scene is blocked, no point is recorded. In [3] the effect of occlusions is mitigated by explicitly determining the overlap in a repeatedly scanned scene of a metro tunnel. At locations where corresponding planar segments were found, apparently no large change took place like the placement of platform furniture. But at these overlapping locations still a detailed deformation analysis can be performed to identify possible subtle changes at the millimeter level due to e.g. changing moisture conditions.

D. *Point-wise deformation analysis*

Point-wise deformation analysis aims at quantifying changes at the level of single point locations. These locations may be the individual scan points of one epoch, or may be grid point locations of some regular grid. In both cases no features like cars, boulders or traffic signs are identified before applying the deformation analysis.

Point-wise deformation is illustrated in Figures 1 and 2. In Figure 1, two point clouds sampling two different sailboats of the Laser Class are shown. As this is a one-design class of boats, two different boats should still have a very similar shape. To verify that similarity for these two boats, both were scanned and the resulting point clouds were cropped such that only points representing the respective boats remained. The two cropped point clouds were subsequently registered using the Iterative Closest Point method [1]. After that the distance of each point p of the second point cloud to the first point cloud was determined by (i) finding the point q in the first point cloud most close to p, and, (ii), determining the distance of p to a plane fitted through a suitable local neighborhood of q. The resulting differences are shown in Fig. 2, where red corresponds to small differences and green to larger differences, still only in the order of a few millimeter.

In [4] a sandy beach is scanned several times from a fixed position by a terrestrial laser scanner. Such scanner operates in a spherical way. Variation in the horizontal plane is obtained by the rotation of the scanner head around its vertical axis, while variation in the vertical plane is obtained by a fast rotating mirror. If such scanner is placed over an almost flat surface like a beach the local point density will decrease rapidly with increasing distance to the scanner. Therefore a subdivision of the point cloud in a Cartesian 2D grid will also result in a large variation in the number of scan points per grid cell. This variation can be avoided by using a spherical grid similar to the organization of a panoramic scan in a depth or range image. A range image is an image where the pixel values represent ranges and the pixel locations corresponds to the way in which the ranges were acquired. For a panoramic scanner the pixel location corresponds therefore to the horizontal and vertical angle at which a range is determined.

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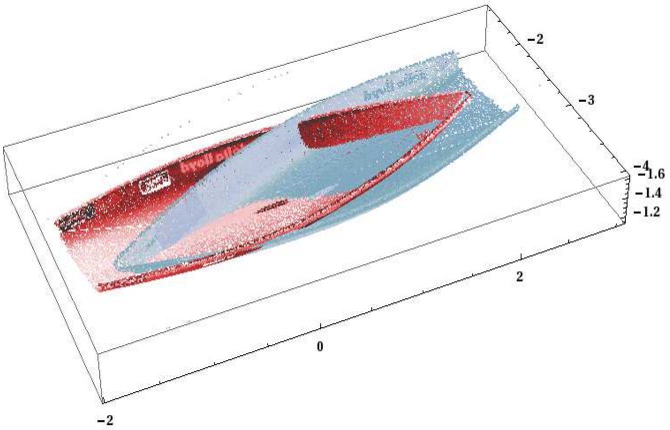

Figure 1. Point clouds of two different Laser Class sailboats.

In the beach example time series per spherical pixel were analyzed for change. In [5] a similar organization in a range image is used to efficiently detect changes on a repeatedly scanned building façade. A large advantage of working with range images is that it reorganizes an irregular point cloud in a regular image or array which enables fast neighborhood identification. Therefore the use of range images is one approach to cope with large data volumes.

E. *Object-oriented deformation analysis*

The strong point of laser scanning is its ability of acquiring a large number of single points sampling the geometry of a scene in a short time. A static scanner typically acquires millions of 3D points in a few minutes. Many man-made infrastructure consists of a concatenation of geometric primitives like notably planes and cylinders. Planes form streets and walls and roofs of houses while cylinders form poles of street furniture and pillars supporting buildings. A point cloud representing a flat wall sampled at 6 meter by a static or mobile laser scanner will also consist of hundreds of thousands to millions of points. Still only three points not sharing a line are sufficient to uniquely define a plane.

This large measurement redundancy demonstrates the potential of laser scanning for object-oriented analysis. In this case the objects are either the components corresponding to a single primitive, like one flat wall, or one cylinder as part of a light pole, or complete objects like a full façade, possibly composed from several walls and or a complete streetlamp.

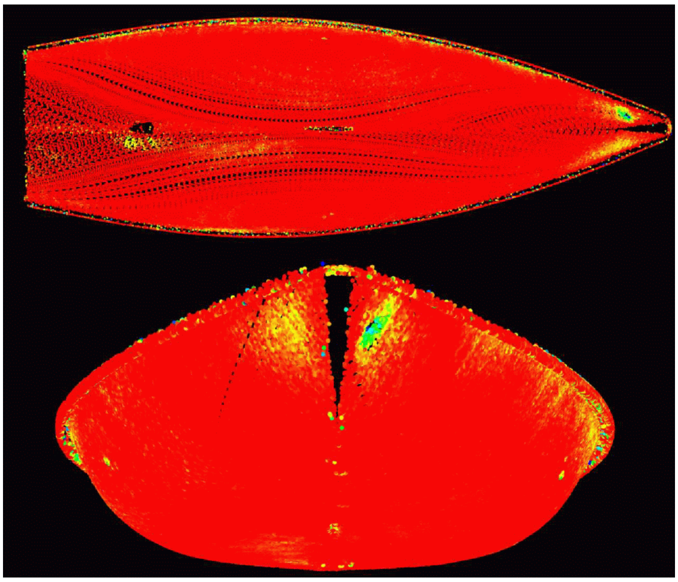

Figure 2. Point-wise differences between the two point clouds in Fig. 1, after registration.

F. *Morphological maps*

In [6] the notion of morphological map is used to identify seismic-induced building deformations. A morphological map consists of the point-wise deviations from a geometric primitive like a plane or cylinder. In that sense I consider this method as belonging to the class of object-oriented deformation analysis. The advantage of considering deviations with respect to such primitive is that point cloud registration is not required: if point clouds from two epochs are available, the deviations from the geometric primitive in the first epoch are simply compared to the deviations to the corresponding primitive in the second epoch and a direct cloud to cloud comparison is not necessary.

In [6] it is even argued that it is not necessary to sample a scene before and after an event like an earthquake to identify changes. Most buildings are constructed anyway in such a way that walls are vertical and planar and therefore deviations in the plumb line or in the local planarity of walls can often be related to the impact of high energy events such as an earthquake, notably if there is additional information available considering the state of a building before the event.

G. *Links to structural analysis of detected deformation*

As the field of laser scanning matures, more articles linking laser scanning to other applications appear. Three such examples are [7], [8] and [9]. In [7] it is described how terrestrial laser scanning is used for the application of damage detection and volume change analysis for a full-scale structural test in a laboratory setting. [8] considers deformation on towers as does [6], but this paper explicitly links the deformation as measured from the scan data to theoretically expected deformation as obtained from a Finite Element Model (FEM) analysis of the possible impact of a sequence of seismic events. In [9] a combination of laser scanning, close range photogrammetry, ground penetrating radar and FEM is described to document the structural state of historical arch bridges.

H. Incorporating measurement geometry

As stated above, [6] discusses the possible deformation of high medieval towers. These towers with heights of sometimes close to 100 m were scanned from a low position with inevitably leads to an unfavorable incidence angle [1]. As the expected deformation signal in the study in [6] was also relatively small, a detailed study of the impact of the incidence angle on the signal to noise ratio is incorporated in the deformation analysis by considering point-to-point differences between scans from the same wall but acquired from different scan locations. Therefore this paper is a good example on how progressing knowledge on the impact of measurement geometry on the data quality should be incorporated in a measurement setup.

I. Sensor Fusion

There are different ways in which sensors can be fused to aid in the detection of deformation. [10] describes a method to obtain deformations in tunnels where projected laser pulses are photographed and converted to a 3D profile in a photogrammetric procedure. This method is quite similar to the principles that are applied in range cameras. A completely different fusion approach is described in [11]. In this paper scan data obtained before and after a landslide are compared to obtain an estimation of local erosion and deposition volumes. What makes it interesting is that the first acquisition was made by airborne laser scanning, while the second acquisition used terrestrial laser scanning. Comparison of the data was hampered by the presence of dense shrub vegetation which had to be removed by an advanced filtering approach. In general the large difference in looking angle during data acquisition may cause problems when combining airborne and terrestrial data as areas where overlap occurs may be hampered by unfavorable scanning geometry.

III. CONCLUSIONS

In this report a short review of recent methods aiming at detecting changes from laser scan data is given. Meanwhile literature on a variety of methods and applications is available. When starting a project first the signal to noise ratios should be assessed. That is, an inventory should be made of the expected changes compared to the expected quality and redundancy of the point clouds. If the expected changes are large and obvious, a straightforward and efficient method can be used that ignores the data quality. If on the other hand, changes are expected to be small, the measurement geometry is unfavorable and outcomes are critical, a careful measurement setup is needed in combination with a possibly stochastic approach that systematically propagates quality of the input data towards the results, by considering the local effect of each processing step. It should also be considered if it is possible to leave out some typical processing steps like registration, to avoid the additional uncertainty it will introduce to the work flow.

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