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Laser scanning as a tool for monitoring road deformations in Svalbard

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ABSTRACT

A key feature of the Arctic environment is permafrost, which is sensitive to climate change. Increasing air temperatures lead to warming and degradation of frozen soils, and increased permafrost temperatures change geotechnical parameters and can lead to infrastructure instability. These processes are particularly prevalent in roads, where natural surfaces are replaced by asphalt, which has a completely different albedo and thermal conductivity.

Climate warming makes the investigation of road deformation in Arctic settlements particularly relevant, as transport infrastructure maintenance is extremely expensive and is critical for settlement operations. Deformation detection and monitoring, using traditional geodesic methods, is difficult and not effective due to road extent and the necessity of frequent measurements. Laser scanning is one of the most promising methods for examining linear infrastructure such as roads.

In this study, a Riegl VZ-1000 laser scanner was used to study road deformations in Longyearbyen, Svalbard. This laser scanner has a high accuracy (5 mm) and allows for surveying from one point at a distance of 800 m. The obtained point clouds were processed to produce 3D models of the main roads in Longyearbyen. The comparison of surfaces obtained from three surveys (conducted in October 2017, May and October 2018) allows for the identification of deformations, monitoring of changes, and determination of the most problematic areas.

The scanning techniques, processing, and visualisation methods used to study the roads of Longyearbyen are discussed in this paper, as well as main features of permafrost degradation and transport infrastructure deformation.

KEY WORDS: laser scanning, infrastructure, permafrost, permafrost degradation

INTRODUCTION

Permafrost is a key characteristic of the Arctic environment and is sensitive to climate warming. An increase in air temperatures, which is pronounced in the Arctic regions, leads to warming and degradation of frozen soils. Increasing permafrost temperatures, in turn, lead to changes in geotechnical parameters, which creates problems for buildings and infrastructure.

The northernmost town of Longyearbyen, located in the Svalbard archipelago, is a “world leader” in global warming (NCCS, 2019); air temperatures are increasing significantly in this region. Given the observed warming, monitoring infrastructure for deformations caused by cryogenic processes is particularly relevant. Monitoring linear infrastructure with traditional geodesic methods (such as leveling) is difficult due to the large and distributed extent of linear infrastructure. Thus, new approaches and methods are required for detecting deformations. One of the most promising methods for examining expansive infrastructure is laser scanning, which was successfully used to investigate runway deformations (Barbarella et al., 2017) (Marchenko, 2018). We used a Riegl VZ-1000 terrestrial laser scanner (Riegl, 2017) to study the deformations occurring on the roads in Longyearbyen. Three field scanning campaigns, conducted in October 2017 and May and October 2018, yielded 3D-models of the main roads in the city and allowed us to identify roadway deformations and track changes in the road surfaces. We also developed scanning procedures and point-cloud processing methods which are applicable to other linear objects in the Arctic environment.

CLIMATE AND PERMAFROST CONDITIONS IN SVALBARD

Deformations of roads and the airport runway are very visible in Longyearbyen, and create difficulties for the local industry and community. Existing studies indicate a significant increase in air temperature: for example, according to (ACIA, 2004), the increase in mean annual temperature in the region from 1954-2003 exceeds 3.0˚C. The rapid increase in Svalbard air temperatures is also mentioned in the IPCC report, where the increase in mean annual temperature for the period 1986-2005 is estimated to be 3.0˚ to 4.0˚C. Projected temperature increase through 2081-2100 may reach 8.0 to 9.0˚C (IPCC, 2014). The Norwegian Centre for Climate Services (NCCS, 2019) also reports a significant increase in air temperature. According to measurements from 1971-2000 at the Longyearbyen airport meteorological station, the average annual air temperature was -5.9˚C, and there was an average of 241 days each year with negative air temperatures. Calculations of these same parameters for 2071-2100 (using the CCLM model, based on the most negative climate scenario RCP 8.5) show that the average annual air temperature in Longyearbyen might increase by 6.5˚C (making the average annual air temperature positive), and the number of days with negative temperatures will decrease by 96 days (NCCS, 2019).

Longyearbyen is located in the coastal part of Western Spitsbergen, where permafrost has the highest temperatures (Romanovsky et al., 2010) and the thinnest thickness in the archipelago; permafrost thickness in the coastal valleys is about 100 m (Liestøl, 1977). Increases in permafrost temperatures have been recorded in the last 20 years in many northern regions: Alaska, Canada, the Russian Arctic, and, in particular, Svalbard (Romanovsky et al., 2017). According to measurements in the Longyearbyen area, permafrost temperature increase at the depth of zero annual amplitude from 2008-2009 to 2016-2017 ranged from 0.4 to 0.5˚C. Warming rates at a depth of 10 m for various sites range from 0.06 C to 0.15˚C per year (NCCS, 2019). Simulation of permafrost temperatures in 2071-2100, using scenario RCP 8.5, indicates that by the end of the century, permafrost temperature at 5 and 10 m depths can approach 0˚C.

In addition to increasing permafrost temperatures, increasing air temperatures lead to active layer thickening. According to the RCP 4.5 scenario, active layer thickness near Longyearbyen may increase by 1 m (from 1.5 to 2.5 m) by the end of the century (NCCS, 2019).

THE USE OF LASER SCANNING FOR THE STUDY OF ROAD DEFORMATIONS

Climate and permafrost changes stimulate deformations of buildings and infrastructure which have been designed for completely different soil parameters and without taking into account climate change trends. Linear objects (roads, pipelines, runways, airfields, etc.) are most vulnerable to deformation. Due to the large extent of such objects, it is extremely difficult to completely avoid building on areas with unfavourable geocryological conditions. Additionaly, the design and construction of infrastructure can activate dangerous cryogenic processes. For example, damming surface water flow paths with road embankments and pipelines can cause ponding, which leads to thermokarst development. In winter, the roads and runways of airfields are cleared of snow and, consequently, lose heat-insulating cover. As a result, there is more pronounced freezing of soils under these objects, and the amplitude of soil temperature during the year increases, leading to intensified frost heaving (Watanabe et al., 2013) and frost destruction.

It is necessary to study and monitor deformations occurring at existing facilities to minimize the detrimental effects of cryogenic processes. The collected data can be used for modelling and future investigations. In the case of buildings and other structures, it is possible to monitor deformations using geodetic surveys of deformation marks. Ground temperatures can be monitored using thermometric wells. However, the large extent and area of linear infrastructure limits the use of classical geodetic methods and requires new approaches.

We used a RIEGL VZ-1000 laser scanner (Fig. 1) to examine linear infrastructure in Longyearbyen. This device has a high measurement accuracy (5-8 mm) and allows for 3D point clouds to be obtained at a distance of 800 m or more. The average time required to survey from one point is from 5 to 15 minutes depending on the selected scanning parameters. Scanning an object returns a “cloud” of millions of points, oriented in space relative to each other, which greatly improves the precision of measurements. The scan result is a 3D terrain model oriented in space.

The RiSCAN PRO programme is designed to process the obtained point clouds (Riegl, 2016) through adjustments, filtering, triangulation, basic measurements, and export to other common software formats (e.g. Adobe, Autocad, CloudCompare, etc.). In these programs, we can compare scans made at different times and evaluate change in surface height. Additionally, surface profiles can be constructed. The spatial resolution of the resulting 3D models is significantly higher and more realistic than that of the “traditional DEM” (Fig. 2).

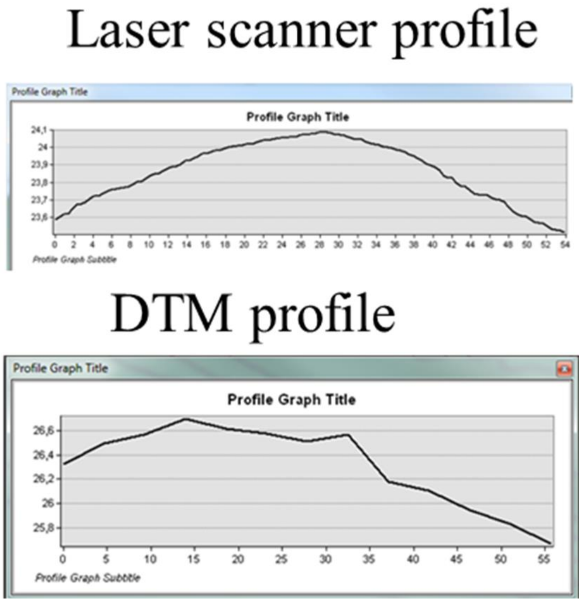

Fig. 1. Laser scanner RIEGL VZ-1000

Fig. 2. Transverse profiles of the Longyearbyen runway created from laser scanning and a Digital terrain Model (DTM) (Marchenko, 2018)

The first trial scan to determine deformations on linear objects was carried out in the autumn of 2017. In 2018, scans were repeated in May and October. In addition to the Longyearbyen airport runway, scanning was carried out on the main roads in the city at 17 selected points. The choice of points was made to provide maximum coverage of main streets and roads. In this paper, we analyze data from scanning performed on two key areas where repair work was carried out in the summer of 2017. At these locations, the surface was levelled as much as possible and fresh asphalt was laid (Fig. 3). This gives us the possibility to monitor deformations from the infrastructure's initial state. During two scan sessions (in May and October 2018), the following scanner settings were found to be optimal for linear infrastructure (roads and runways): maximum scanning distance of 900 m, with horizontal and vertical steps of 0.03°. These settings provide a fairly dense distribution of points on the surface of the surveyed object and avoid capturing "excess" surrounding objects, which simplifies point cloud processing.

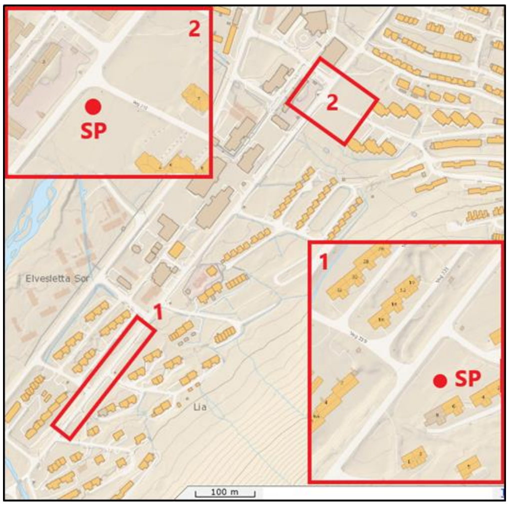

Fig. 3. Location of scan areas

LASER SCANNING PROCESSING METHODS

Point cloud processing was performed in the programs RiSCAN PRO and CloudCompare. RiSCAN PRO is the program created and supported by Riegl; it requires license and dongle access. Raw Riegl scans can only be opened and processed in RiSCAN. CloudCompare is an open-source platform for various types of 3D point clouds and mesh processing (CloudCompare, 2018). These programs provide a wide range of tools for handling point clouds. Coloring point clouds by height is the simplest way to initially assess irregularities and deformations on linear objects, as main topographic features can be identified.

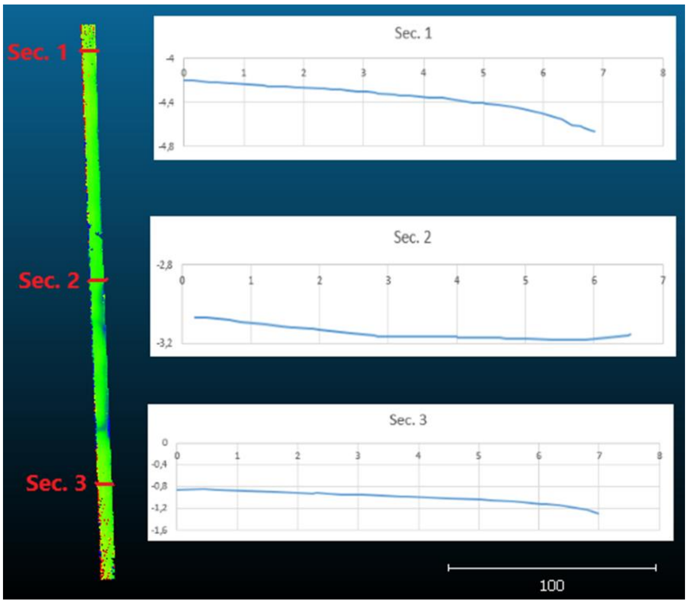

Fig. 4. Cross profiles along location 1

Coloring by height only identifies large (several meters) irregularities on the surface of the surveyed object. For the analysis of smaller irregularities and deformations, this method is not suitable. The most obvious method for studying surface micro-relief is the construction of height profiles. The point distribution gives an overview of the general relief of the scanned object, but also allows for irregularities to be identified on the centimeter scale. Both CloudCompare and RiscanPro provide this operation. Three transverse profiles of the road in area 1, created in CloudCompare, are presented in Fig. 4. The high density of points makes the profiles built with scan data informative and representative of the detailed road surface relief. In CloudCompare, it is possible to create profiles of arbitrarily defined lines, so the most "interesting" sections can be studied in detail. For example, a longitudinal profile was created for a pavement section (25 m long) where road subsidence was detected when comparing different scans. The location and magnitude of subsidence is perfectly visible on the constructed profile (Fig. 5).

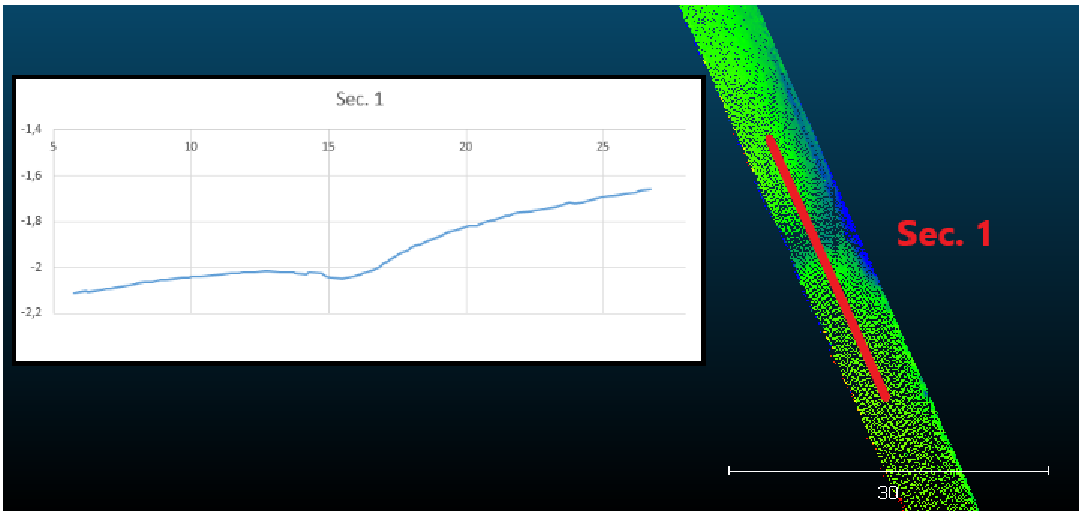

Fig. 5. Longitudinal profile of the road surface in the area of pavement subsidence

The density of the points obtained during scanning may be excessive. Some points may represent "noise" – interference arising from precipitation during scanning or movement of objects – and should be cleaned up. In some cases, point cloud thinning is necessary (Fig. 6). Both programs have a similar tool (2.5D Raster filter) for this purpose. When the filter is applied, the entire point cloud is divided into a square grid with a given size, and all points beyond the grid nodes are removed. In addition, when the grid parameters are set, it is possible to filter the points by height relative to the average surface. During processing, we filtered points using minimum heights to remove excess terrain. In regards to linear infrastructure, minimum heights always correspond to the real surface of the object. A point cloud thinned with the 2.5D Raster has sufficient accuracy to detect significant irregularities in the object's surface without overloading computer processing power, and thus maximizes efficiency.

The comparison of models obtained from scans taken at different times allows not only the evaluation of already existing irregularities and deformations, but also makes deformation tracking possible. Repeated profiles and a variety of other tools can be used for comparison. One such tool is “Surface comparison” in RiSCAN PRO, which evaluates changes in surface height by comparing two different 3D-models. To use this tool, it is necessary to triangulate at least one of the point clouds, since comparison is only possible in one plane at a time. A similar procedure is possible in CloudCompare. To compare two scans, one of the scans must be transformed into a planar view (this requires a triangulation procedure, for example, Delaunay 2.5D triangulation).

We used these methods to compare scans of the road in area 1 (Fig. 3), taken from the same point in October 2017, May 2018, and October 2018. Sequential comparisons were made between October 2017 and May 2018, and May 2018 and October 2018. Comparison of the scans from October 2017 and May 2018 revealed up to 6 cm of subsidence of the roadway across the entire width of the road (Fig. 6).

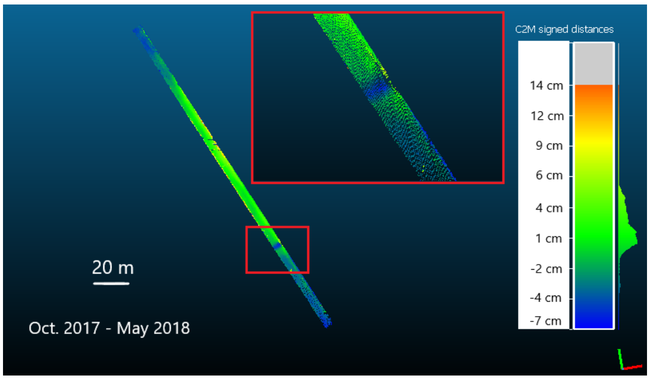

Fig. 6. Comparison of area 1 road surface elevation between the scans from October 2017 and May 2018.

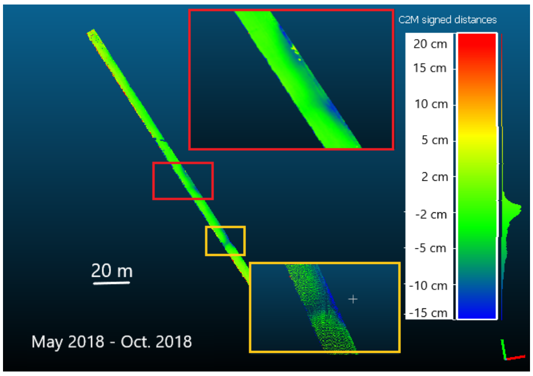

Fig. 7. Comparison of area 1 road surface elevation between the scans from May and October 2018.

Comparison of the scans from May 2018 and October 2018 showed a significantly greater number of roadway deformations. The previously identified subsidence area increased in depth by another 6-7 cm and widened along the right side of the road. In addition, a new area of subsidence was identified in a stretch of pavement along the right side of the road. The greatest subsidence occurred along the road's edge, where change in surface height reached -10 to -15 cm (this was observed in two distinct patches). There was less subsidence closer to the center of the road; on average, subsidence ranged from -5 to -7 cm (Fig. 7). Greater changes in the height of the road surface between May and October 2018 can be explained by active layer thaw during the summer and ground ice melting.

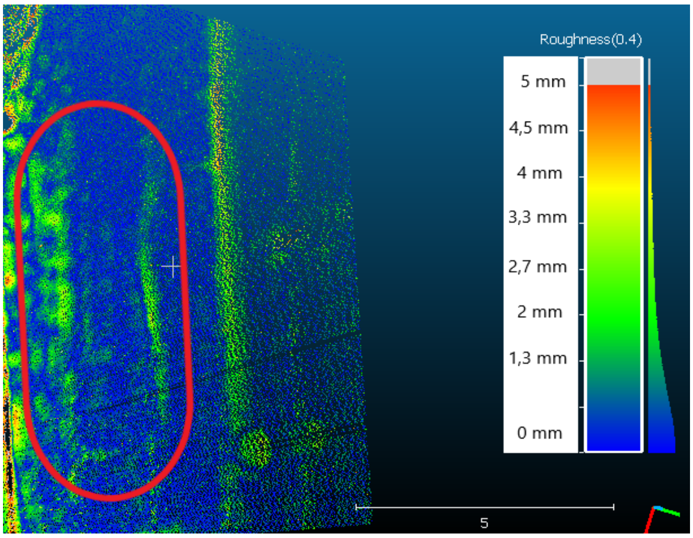

Fig. 8. Road segment with ruts 3-4 mm deep, visualized by calculating surface roughness.

Another method for detecting deformations is to determine the mathematical roughness of the surface. For each of the points obtained via scanning, a "roughness indicator" is calculated, which represents deviations from the plane in which most of the surrounding points lie. The radius in which the deviation is estimated is set by the user, allowing for analysis of surface deformations at various scales. With a smaller radius, smaller deformations will be noticeable. For example, with a radius of 0.5 m, very insignificant deformations and irregularities are visible, such as ruts on roads (seen in area 2) with a depth of less than 2 mm (Fig. 8). The main disadvantage of this method is that the roughness indicator only has positive values. Thus, both surface subsidence and buckling (i.e. downward and upward displacement) are indicated in the same way as a deviation from the average surface. To determine the vector of irregularities, manual processing and interpretation is required.

Fig. 9. Flooding along the road in Longyearbyen

The identified deformations on the roads of Longyearbyen can be explained by changes in geocryological conditions and cryogenic processes activated by climate warming and anthropogenic activity. Temperature increase in frozen soils leads to a decrease in strength and load-bearing capacity and an increase in active layer thickness (NCCS, 2018). Increase in active layer thickness increases frost heaving processes in the winter and subsidence during the thawing period. These processes are not evenly spatially distributed. The magnitude of subsidence and heaving depends on soil moisture, which varies under the road surface. Another reason for road deformation in Longyearbyen is man-made flooding along road embankments. Under the roads, a frozen core is formed (due to more intense freezing in winter caused by the clearing of snow from the roads), which prevents runoff and infiltration of surface and groundwater. Poor construction design and culvert failure can lead to flooding along road embankments; this phenomenon is common in Longyearbyen (Fig. 9). The warming effect of ponds further weakens frozen soils, increases active layer depth, and can lead to thermokarst development. As a result, road subsidence is greatest along the road shoulders, as seen in Figure 7.

CONCLUSIONS

Laser scanning is a promising method for monitoring deformations of linear infrastructure due to their large extent, and the limitations of using traditional geodetic methods. The accuracy of 3D-models obtained via scanning is much higher than the accuracy of digital elevation models, and deformations can be identified on the centimeter and millimeter scale. Extensive processing tools (automatic comparison of surfaces, creation of elevation profiles, calculating parameter irregularities, etc.) provide ample opportunities for interpreting scan data. Scanning the same object at different times is a valuable procedure and allows for subsidence and heaving to be detected and morphologically described with high accuracy.

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