GAINING AREAL DEFORMATIONS BY USING DRIVING-ATTENDANT LASER SCANNING FOR THE NEW AUSTRIAN TUNNELLING METHOD

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Abstract: A prompt and reliable knowledge concerning areal deformation behaviour of an excavated tunnel intrados and/or the heading face embodies a valuable data source for tunnel construction and design, especially for the feedback-based New Austrian Tunnelling Method (NATM). The validation and adaption of implemented support elements and design parameters, quality control, complete areal conservation of evidence, observation of the rock mass behaviour and the enhancement of security levels are the most important benefits so far. Furthermore cost savings and economies of time can become possible by means of support optimisation. Not yet applied on construction sites, areal deformations from laser scanning datasets for these purposes of NATM-tunnelling are matter of actual research in engineering geodesy in cooperation with geotechnical research at the Technische Universität München. A in this context recently developed and software-implemented computational approach shows an effective and reliable way to derive and visualise areal deformations of the tunnel intrados or the heading face, independently of the excavation geometry. The computational algorithm is verified on spatiotemporal 3D point cloud data (driving-attendant laser scanning data)[1]. The main parts of the computational approach show a point-wise tunnel tape transformation, a common difference model based on a Delaunay triangulation and as new approach an adaptive data filtering technique achieving a reliability improvement in the resulting deformations by eliminating pseudo-deformations. The filtering algorithm is based on regional and adaptive confidence regions. The algorithm can be understood as semi-automatic workflow, showing the potential of a close real-time application on-site.

1. The New Austrian Tunnelling Method (NATM)

Before dealing with driving-attendant laser scanning in tunnelling and elucidating a method to gain and visualise areal deformations of a tunnel intrados, the main features of the New Austrian Tunnelling Method (NATM), as design and construction method for tunnels, are subsequently illustrated.

The NATM [1] has been developed by Austrian engineers such as Rabcewicz, who already patented an appropriate support concept for tunnelling in 1948. The characteristic application

[1] The author's diploma thesis (outcomes presented in this article) has been supported by the GEODATA Group in Leoben, Austria, allocating appropriate laser scanning datasets and by the Civil Engineering Office Stuttgart (Tiefbauamt Stuttgart) offering the opportunity of further laser scanning measurements

of a thin sprayed concrete (shotcrete) lining on the tunnel intrados, directly after excavation, gives the NATM also the name “Sprayed Concrete Lining Method” (Figure 1). One of the key features is the development of a maximum self-supporting capacity of the surrounding rock (transformation of the surrounding rock into a self-supporting arch) by avoiding loosening pressures. The benefit of shotcrete as a support concept against loosening in the bedrock lies in its direct interaction with the neighbouring rock mass. The shotcrete lining can be systematically reinforced by lattice girders or steel arches, fibre, welded wire mesh and sometimes ground reinforcement (e.g. rock bolts) and is closed at the earliest possible moment by an invert to a complete ring. Allowing controlled deformations of the tunnel intrados are a common practice in NATM-driven tunnels. Beside the magnitude of these radial deformations, it is of substantial interest when deformations reach equilibrium. Monitoring systems [2] and conventional displacement monitoring [3] can verify design assumptions, calibrate numerical models and guarantee quality control. The shotcrete lining as temporary support is supplemented by an inside lining, built as regular concrete construction.

Figure 1: NATM-driven tunnel

2. Established NATM-laser scanning applications

There exist numerous structural laser scanning applications for NATM-driven tunnels. Not least to a fast developing laser scanning technology [5], new applications have been generated and have become possible in the last years. It is necessary to distinguish between static and kinematic laser scanning. Static laser scanning as used for structural assistance covers the determination of profile compliances (over- and underbreak visualisations), volume and thickness calculations of shotcrete linings and the geological assessment of the heading face in combination with photographic data. Best suited for these applications are flexible, static laser scanning systems – like the Orthos Laser Tunnel Scanner [6] – with potential of on-site analyses. Beside structural applications, driving-attendant laser scanning has the ability to provide data for structural quality management. A direct confrontation of laser scanning data before and after the application of shotcrete on the tunnel intrados gives information about the shotcrete coefficient (shotcrete rebound), using a direct volume comparison. Also a possible thickness optimisation of shotcrete layers and undulation analyses contribute to the task of structural quality management. As a coproduct, driving-attendant laser scanning datasets produce a all-over structural conservation of evidence concerning a documentation of support-elements for instance. Figure 2 gives an overview of tunnel scanning applications in general, considering the tunnel life cycle phases.

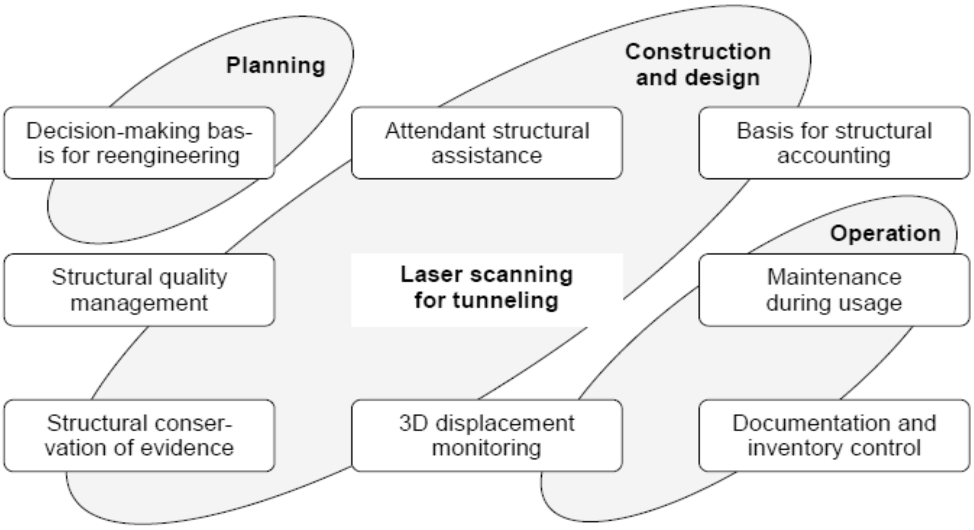

Figure 2: Fields of application for laser scanning in tunnelling with reference to the tunnel life cycle

3. Driving-attendant laser scanning

A driving-attendant laser scanning system is integrated into the tunnel driving process without causing significantly long standstills during the tunnel construction process. To guarantee economical and complete three-dimensional measurements of the intrados and/or the heading for documentation of different construction phases, the system is positioned autonomously (e.g. using existing reference points) and features an on-site quality control of the positioning.

Figure 3: Driving-attendant laser scanning with the Orthos Laser Tunnel Scanner [6]

The scanning result is a complete area-wide geometrical documentation of the raw excavation profile or of the shotcrete profile, available in the existing project coordinate system directly after the measurement – automatically visualised and statistically analysed by appropriate analysis software. Driving-attendant laser scanning can be seen as an approach of systematic deformation-monitoring.

Therefore and for all other criteria met, the Orthos Laser Tunnel Scanner (Figure 3) can be described as a driving-attendant laser scanning system for the previously mentioned applications [6].

4. Areal deformations from driving attendant laser scanning data

Basis for analysing areal deformations of a tunnel excavation are multi-temporal 3D-point clouds with an overlapping band on the tunnel intrados (Figure 4). Obviously, positioning uncertainties directly flow into the examination of deformations as systematic uncertainty. Thus it is essential to optimise the positioning accuracy to be able to verify small statistically significant deformations.

Aside from still existing accuracy limitations, laser scanning definitely has diverse advantages compared with the established forms of geodetical displacement monitoring in NATM-driven tunnels like invar tape measurements or three-dimensional displacement monitoring with total stations. A prompt gaining of deformation-data directly after shotcrete-application is possible without the time-consuming installation of measurement targets in rearward areas of the tunnel excavation. In case laser scanning is already used for any of the above mentioned established applications like checking profile compliances, deformation data could be provided as “coproduct” without causing one minute more standstill on the construction site due to the laser scanning measurement itself.

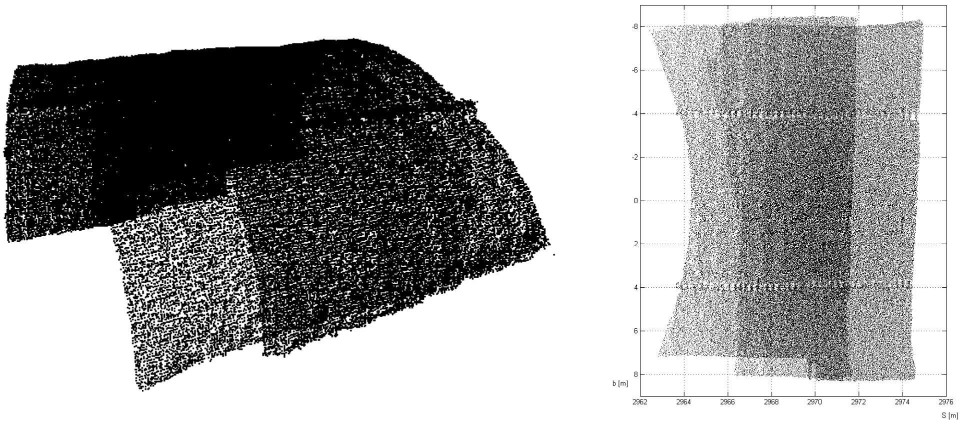

Figure 4: Multitemporal 3D-laser scanning data of a tunnel intrados (right: tunnel tape)

In principle, one can distinguish between three difference-models as basic elements to gain object-deformations out of multi-temporal three-dimensional point data, concerning deformations of structures like for example tunnels, bridges or locks:

1. Point-wise grid-interpolated 2,5D-approaches [4],[8],[9]
2. Geometrical comparison of section-wise best-fit surfaces [10], [11],[12]
3. Discrepancy using approximated parametric surfaces [7]

In the following the first approach is used to gain areal deformations of a tunnel intrados, as presented in the next sections.

4.1. Pointwise tunnel-tape transformation

For NATM tunnels, the theoretical cross-section profiles are compound curves with different cross-section sectors. A grid-interpolated 2.5D-approach using cylinder coordinates [9] is not regarded suitable by reason of a suboptimal standardisation of deformation-directions. Due to an asymmetric geometry an unwinding of the point-data along the theoretical cross-section profile guarantees real radial deformation directions on the tunnel intrados. Tunnel tape coordinates consist of the stationary S along the tunnel axis, the laterally unwinding b orthogonal to the tunnel axis, considering the valid cross-section profile and the derived profile deviations δ. The project coordinate system (Y, X, H), the local scanner coordinate system (x_S, y_S, z_S) and the profile coordinate system (x, y, S) embody intermediate steps of partial transformations (Figure 6).

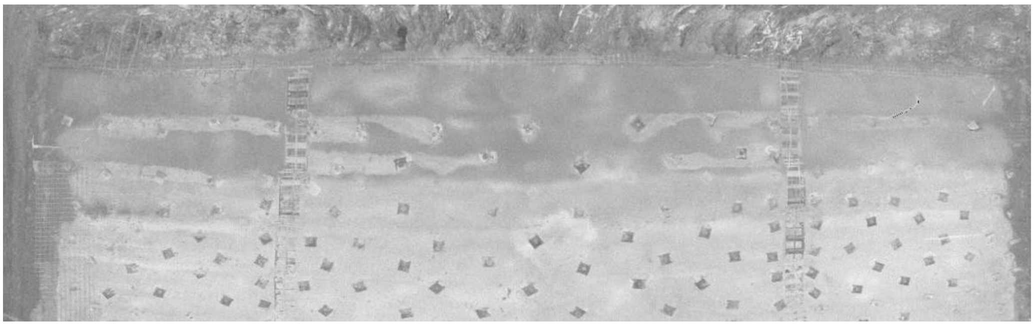

Figure 5: Unwound laser scanning data of the tunnel intrados (intensity coloured)

The unwound data can be visualised as tunnel tape (Figure 4, right and Figure 5). A tunnel tape stands for a length-preserving map with existent isometry. Each measurement point is attributed with the orthogonal deviation from the valid theoretical profile.

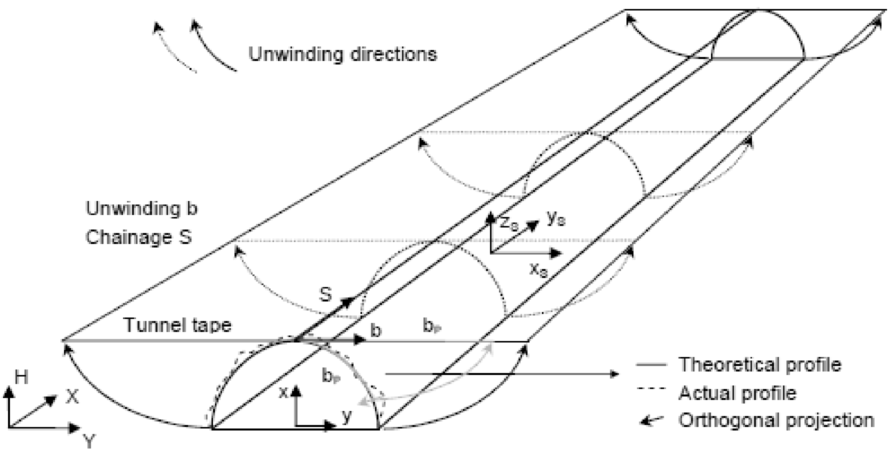

Figure 6: Pointwise unwinding of the laser scanning data along the cross-section profile, simplified for a circular arc as theoretical profile

The unwinding of multi-temporal point clouds into a tunnel tape is the basis for the following approach of gaining deformations. The attributed height component allows a 2.5-dimensional derivation of radial deformations within the whole dataset. The unwinding can be regarded as point-wise transformation avoiding any interpolation or central projection mapping the point data into the tunnel tape plane.

4.2. Radial deformations from 2.5D-difference model

Within the tunnel tape the unstructured 2.5-dimensional point data has to be interpolated on a regular grid, in order to create artificial identical points in a fixed reference frame. By using the Delaunay-Triangulation the result are interpolated deviations δ_i for all grid points. The grid spacing is adapted to the mean point density within the point cloud; also a respective expanding of the grid space might be suggestive but not used so far. Thus the results of differences $\Delta\delta_i$ for interpolated grid points in multi temporal datasets embody radial deformations. According to [12] the parameter noise n_i and systematic uncertainties e_i have to be considered for the 2.5D-difference model.

$$\delta_i(2) - \delta_i(1) = \Delta\delta_i + n_i + e_i \tag{1}$$

Already mentioned, systematic position uncertainties directly flow into the parameter e_i, while the noise-parameter n_i can be refined into measurement noise and surface noise as synonym for the surface roughness of shotcrete.

4.3. Elimination of pseudo deformations with regional adaptive filter

One has to distinguish between deformations of the excavated tunnel intrados and artificial alterations of shape concerning the tunnel surface. There are some reasons for artificial alterations of shape, named in the following “pseudo deformations”, which can be seen as erroneous data and gross errors: New installed support elements like anchor plates, additional shotcrete application, material removal or foreign objects, to name just a few examples (Figure 6, left).

Due to different regional deformation levels $\Delta\delta$, a global threshold is not applicable in this context. The automatic elimination of above described pseudo deformations within the derived deformations $\Delta\delta_i$ has to be resolved with a regional adaptive approach including regional deformation levels. To start with, noise has to be reduced within the interpolated point data in both measurement epochs $\delta_i(1)$ and $\delta_i(2)$, using a low-pass filter like a median-filter, a mean-filter or the applied binomial-filter achieving a noise reduction of factor two to three. After noise reduction smoothed datasets build the input for the deformation model. A measure for the noise level η can be defined as standard deviation of residuals of small scale local best-fit planes. A representative value for the noise level η is derived from empirically-selected test regions without pseudo deformations, as typical surrounding concerning surface roughness and measurement noise of the laser scanner. The regional deformation level $\Delta\delta$ can be derived by maximum extraction within the regional histogram of deformations $\Delta\delta_i$. The size of regional tiles within the tunnel tape coordinate systems defines the regional characteristic of the applied filter and has to be chosen in adequate size, in order to guarantee that pseudo deformations form secondary maxima within the histogram of regional deformations.

Finally the elimination of pseudo deformations is performed by adaptive thresholds. These regional valid thresholds are balanced equally around the appropriate value $\Delta\delta$, while the upper and lower limits are created by adding the triple noise level η. These bounds can be described as a confidence region with a confidence level of 99.73 (triple standard deviation). Confidence regions implicate a Gaussian distributed deformation model, which has been assumed within this context.

$$P\left[-3 \cdot \eta < \Delta\delta_i - \Delta\delta < 3 \cdot \eta\right] = 0.9973 \tag{2}$$

In summary, the regional adaptive filtering algorithm can be described as regional valid and adaptive confidence interval for the elimination of pseudo deformations considering the existing noise level. Figure 6 shows the results of deformations of laser scanning data of a tunnel intrados with a time difference in data acquisition of 22 hours.

4.4. Visualisation

For testing of above described transformations and filtering calculations as well as for visualisation, the Matlab-software offers a good surrounding for programming and plotting of interpolated point data.

The elimination of pseudo deformations allows a reliable statistical analysis of areal deformations on the tunnel intrados (Figure 6, right). Beside an examination of the pure colour-coded visualisation, mean deformation values can be calculated as mean deformation patches. Additionally maximum, minimum and average information concerning the deformations can be calculated.

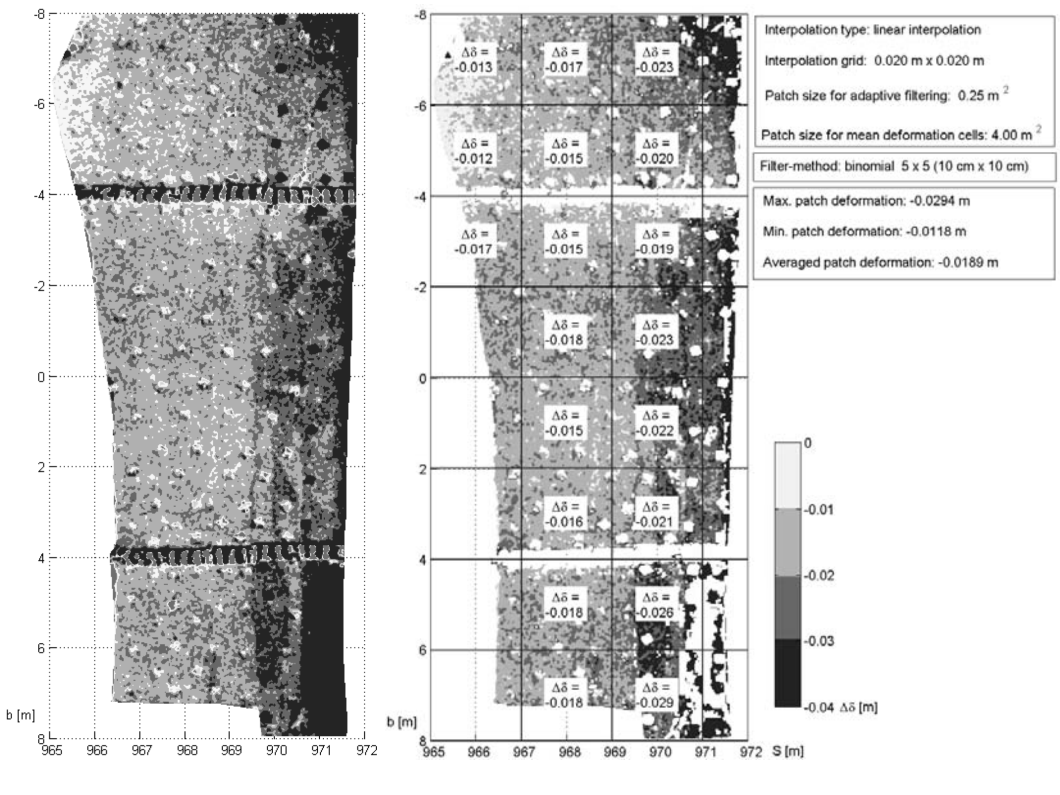

Figure 6: Automatic resolved surface plot of radial deformations, applied elimiation of pseudo deformations, with mean deformation patches for visualisation

Datasets used for the below shown visualisation example originate from a NATM-driven tunnel, acquisitioned with the Orthos Laser Tunnel Scanner [6]. At that time the laser scanner component of the driving-attendant laser scanning system mentioned was a Riegl LMS-Z360i, in the meantime updated to laser scanner technology of actual generation. This has to be considered regarding the on-site positioning and especially the accuracy of the distance measurement component as well as the resulting noise behaviour.

5. Potential and outlook

Gaining areal deformations with driving attendant laser scanning definitly incorporates benefits for tunnel construction, especially for the New Austrian Tunnelling Method. A verification of applied support methods could be surveyed in a better way using complete and areal deformation data. Transfering the calculation method of areal deformations to the tunnel face, further analyses concerning the face stability could be made to estimate the security level with objective deformation data of the tunnel face in a driving-attendant manner.

Furthermore areal deformation values can be used in combination with other established measurement technologies like tacheometric displacement data or extensometer measurements, possibly stored together in a tunnel information system. Geotechnical models concerning tunnel stabilities and predicted deformations can be verified as well. Actual research cooperations with geotechnical specialists show potential of synergetic effects for the future.

In the author's view, the findings. as summarisied in this article, show potential of further research concerning areal deformations from driving-attendant laser scanning data. Topics of further research are the improvement of the free stationing of the laser scanning system in the tunnel environment, an examination of the accuracy potential, an assessment of a reliability and accuracy increasing by filtering techniques as well as the potential of parametric surface approximation for the deviation of deformations .

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