Automated Detection and Interpretation of Geomorphic Features in LiDAR Point Clouds




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Abstract

Laser scanning has proven to be an adequate tool for the acquisition of topographic data. For large scale or even country-wide campaigns, airborne platforms (ALS) are suited, while for small areas, terrestrial laser scanners (TLS) are commonly used. According to the instrument type and the measurement principle applied, more than one million points may be acquired per second. This allows for dense and accurate acquisition of the topography. Unfortunately, the amount of data becomes a considerable challenge for the user of such data. Therefore, often products derived from the original point clouds are provided. For topographic modeling, digital terrain models are commonly used. Such models may be derived by means of robust filtering strategies for separating ground surface points from others representing, for example, vegetation, buildings, etc. Within this contribution, the application of a point-based segmentation algorithm for reducing the amount of data for the purpose of subsequent geomorphological topography analysis is presented. For this, the raw point data is subdivided into planar faces, allowing reducing the amount of data by a factor of up to 3,000 without a significant reduction in the level of detail of the terrain representation. The application of this approach is proven on a series of ALS and TLS data sets acquired at the landslide in Doren, Vorarlberg. By means of additionally recorded geological in-situ measurements it could be demonstrated that geomorphological primary directions can be properly determined within the reduced laser scanning data.

Keywords: Segmentation, Laserscanning, Doren, Geomorphology, Landslide

Kurzfassung

Zur Erfassung topographischer Daten haben sich Laserscanning basierte Methoden etabliert. Für großflächige bzw. landesweite Messkampagnen eignen sich flugzeug- bzw. helikoptergestützte Plattformen (ALS), zur kleinräumigen Erfassung kommen häufig sogenannte Terrestrische Laserscanner (TLS) zum Einsatz. Abhängig vom Gerätetyp und dem verwendeten Messprinzip können mehr als eine Million Punkte pro Sekunde erfasst werden. Dem damit offenkundig verbundenen Nutzen einer äußerst dichten und genauen Erfassung des Geländes stehen aber auch meist enorme Datenmengen gegenüber. Dies stellt den Anwender derartiger Daten häufig vor nahezu unüberwindbare Probleme. Daher werden im Allgemeinen aus den Rohdaten (Punktwolken) abgeleitete Produkte zur Verfügung gestellt. Im Bereich der Topographiemodellierung finden häufig digitale Geländemodelle Verwendung. Diese können mit Hilfe robuster Filtermethoden aus den Originalpunkten abgeleitet werden. Dieser Beitrag demonstriert die Anwendung einer punktwolken-basierten Segmentierungsmethode zur Reduktion der zu verarbeitenden Daten für weiterführende, geomorphologische Geländeanalysen. Dabei wird das erfasste Gelände auf Basis der Rohdaten in ebene Flächen unterteilt. So kann eine Datenreduktion um den Faktor 3.000 erzielt werden, ohne signifikante Einbußen in Bezug auf die Detailliertheit der Geländebeschreibung hinnehmen zu müssen. Die Anwendung dieses Ansatzes wird an Hand einer Serie von ALS und TLS Aufnahmen der Hangrutschung in Doren, Vorarlberg, demonstriert. Mit Hilfe zusätzlich erfasster geologischer Geländemessungen konnte gezeigt werden, dass geomorphologische Hauptrichtungen auch in den stark reduzierten Laserscanning Daten erfolgreich bestimmt werden können.

Schlüsselwörter: Segmentierung, Laser Scanning, Doren, Geomorphologie, Massenbewegung

1. Introduction

LiDAR (light detection and ranging), also referred to as laser scanning, has proven to be an adequate tool for the acquisition of high-density and accurate topographic data (e.g. [1], [2], [3]). If the sensor is carried by airborne platforms (e.g. airplanes or helicopters), it is commonly referred to as Airborne Laser Scanning (ALS). ALS allows for the acquisition of topographic data of large scale areas or even country-wide with decimeter accuracy. Depending on the acquisition geometry (i.e. accessibility and visibility of the area to be captured), for smaller areas Terrestrial Laser Scanning (TLS) is a preferable alternative to ALS. In this case, the scanner is mounted on a tripod allowing, in general, for capturing the panoramic surroundings of the scanning position with centimeter accuracy or even better, dependent on the measurement distance and the surface structure. Current instruments applying the phase-shift measurement principle for distance measurement allow for sampling up to one million points per second [4].

Despite the above mentioned advantages of laser scanning technology, a great number of potential users are limited in its use. A major problem in the application of laser scanning is the enormous amount of data. Up to one million points are captured per second meaning a considerable challenge for the end user of the data even for smaller areas and becoming more and more insuperable with an increasing size of the areas to be investigated. Hence, the experimenter has to have a high degree of data-specific knowledge and experience in order to manage the acquired dataset and to derive the relevant information from raw or intermediate data products. By the way, a considerable processing infrastructure may be required for processing the data within acceptable time. From this, the key research question of this contribution can be defined as the following hypothesis: “Applying an automated plane detection algorithm on large scale LiDAR datasets enables reducing the amount of data for further interpretation significantly without loss of information”.

Within the Christian Doppler Laboratory “Spatial Data from Laser Scanning and Remote Sensing”, assigned to the Institute of Photogrammetry and Remote Sensing of the Vienna University of Technology, a variety of aspects with respect to laser scanning have been investigated for seven years from end of 2003 to end of 2010 including potential solutions to the aforementioned problems. A team of up to ten researchers was financed by all together eleven commercial partners and funded by the Christian Doppler Research Association (CDG). The fields of business activities of the partner companies covered instrument manufacturing, surveying and photogrammetry, geo-data services, cultural heritage management, and stone masonry. Correspondingly, a variety of topics was investigated covering instrument calibration (ALS: [5], TLS: [4]), object extraction [6], geometric modeling [7], and analysis. The produced results exceeded the current industry standards in quality and in quantity, and therefore proved to be suitable to carry out various experiments for future applications.

Among others, a key product delivering possibilities for geomorphologically relevant topics proved to be the digital terrain model (DTM) representing the bare surface of a given area [8]. DTM generation may be based on applying adequate filtering techniques on the original points (e.g. [9]). This allows for separating terrain points from other objects such as vegetation or buildings and subsequently the generation of a DTM. Alternatively, the amount of data may be reduced by aggregating points with similar properties to distinct objects representing the attributes of the original points, i.e. a segmentation of the point cloud. An example for such an application is the derivation of building models from point clouds. In this case, points belonging to planar features are assigned to roof planes as the foundation for the subsequent geometrical modeling process. The assumptions made when assigning points to the plane (i.e. similar aspect and slope, neighborhood, etc.) guarantee that the respective attributes of the plane are similar to those of the belonging points hence representing the information of the original points properly, without significant loss of information. As a matter of fact, the number of objects (in this case the plane faces) is significantly smaller than the number of original points. Therefore, the amount of data to be processed for further interpretation and analysis is reduced significantly, so it becomes usable for most end users.

The segmentation into planes described above, was developed for the analysis of roofs and other man-made surfaces. In this article we study, if and how this segmentation can be used in analysis of natural surfaces. In close cooperation with earth sciences, geomorphologic analysis of the topography at the very high resolution of laser scanning data and derived products provided new and detailed results in assessing micro-topographic features and also changes of these features in time (e.g. [10], [11]). A prominent study area is the landslide of Doren in Western Austria (Vorarlberg). Here, both object extraction and time-series analysis of the extracted geomorphic features could be tested.

2. Theoretical Aspects

The progress made in automated extraction and modeling of buildings from ALS data serves as a promising originator for testing these algorithms for detection and generalization of geomorphic features. Our aim is to recognize automatically as many features as possible from airborne and terrestrial laser scanning point clouds, in order to reduce the amount of data significantly for further geomorphological interpretation. For this, we propose to apply a segmentation process allowing determining planar structures within a surface represented by a point cloud. This allows processing the original point cloud directly without the prior computation of a DTM.

The segmentation is based on a robust calculation of local tangential planes for all recorded points. For this, a set of neighboring points is taken and, by means of a robust plane fit, the fifty percent of points fulfilling best a locally estimated planarity criterion are used to determine the local tangential plane for each point ([12]). For the determination of planar structures in the point cloud it is assumed that similar tangential planes were determined for points belonging to the same planar structure.

Based on checking the quality parameters describing the planarity behavior of such a point set (i.e. the ratio of the axis of the covariance ellipsoid circumscribing the points accepted for the locale plane fit), points acquired at non-continuous surfaces (e.g. vegetation) can be identified and excluded from subsequent analysis. Hence, a prior filtering of the point cloud as necessary for DTM computation as described in [9] is not required in this case. The procedure of segmenting an ALS point cloud representing a house is demonstrated for two planes in Fig. 1 (plane 1: a&b, plane 2: c&d). First, seed regions are determined globally in a feature space defined by the parameters of the local regression planes and using a 4D distance threshold for distinguishing different planes (red circles). Afterwards, all points possibly belonging to this seed plane are assigned using a 3D distance threshold within the object space (orange and light green). Points that do not fulfill the planarity criterion of the seed plane are subsequently rejected applying the feature space threshold again (orange) and finally, a robust plane is fitted into the selected points (dark green). The final segmentation result is shown in Fig. 1 e.

Owing to the design of the algorithm, millions of input points can be processed with acceptable processing time on standard computer systems [7]. For each segment, numerous parameters are derived which can be used for further exploration. These are, for example, location, area, aspect, slope, and roughness. For processing large scale areas with low variety in surface structure with respect to its global extension it turned out to be advisable to apply the segmentation using a tiling structure. Although the feature space distance measure used for investigating the identity of individual planes is scale independent (i.e., the size of the investigated area is normalized by its extension), it turned out that especially the globally applied seed region determination tends to geometrically correct but geomorphologically unreliable results if being applied to large scale areas, especially in areas with low geometrical variety.

3. Data and Methodology

The study area, the Doren landslide, is located in Bregenzer Wald in Vorarlberg, Western Austria in the Foreland Molasse Zone. It can be classified as a deep-seated rotational landslide [13]. The landslide itself has shown several active periods in the last decades, endangering settlements and land property. Geologic units of the area mainly comprise sediments of the freshwater molasses. This area formed a depression zone in front of the over thrusting and northwards propagating Alpine nappe stack. The molasse units consist lithologically of variegated sediments such as sandstones, marls and clays that are mixed up and interbedded. The landscape was subject to glaciation leaving remnants of Würmian moraines. Regional and local topography is highly dissected by river incision. Several watercourses cut into the host rock; the most important of them is the Weißach River, since its incision forms the valley

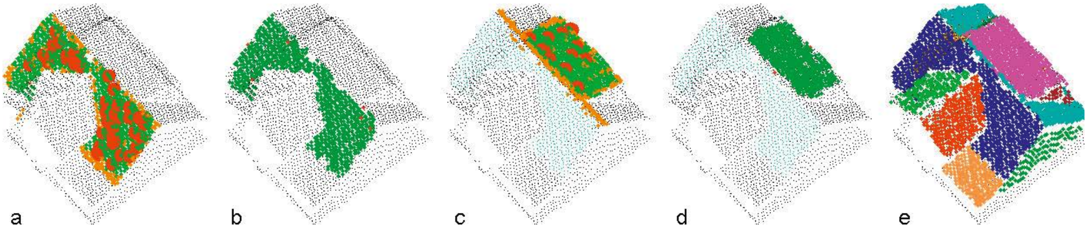

Fig. 1: Detecting planar faces from a point cloud by segmentation, demonstrated on man-made surfaces like roof facets. (a)-(d): Determination of segments 1 and 2. (a) and (c): Seed cluster points (red circles), points accepted in object space (orange and green), points accepted in feature space (green). (b) and (d): Result of robust plane fit (dark green: accepted, red: rejected). Small cyan dots in (c) and (d): points assigned to segment 1. (e): result of the segmentation; black: points of the rejection class not assigned to planes.

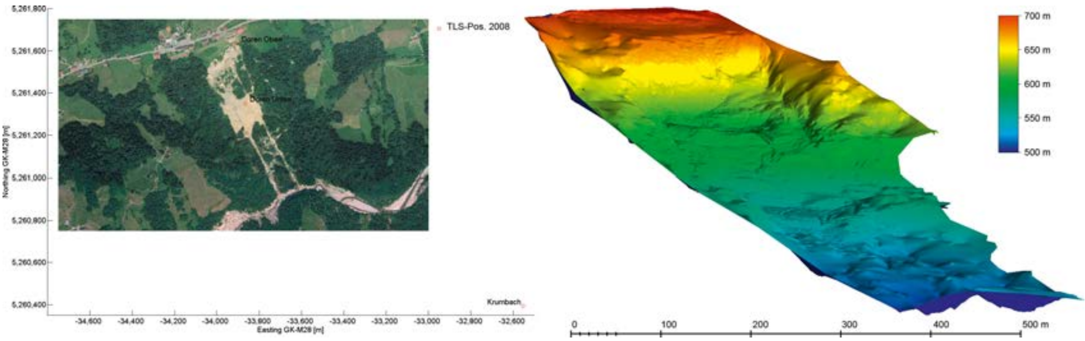

Fig. 2: Orthophoto of the Doren landslide in 2006 and scanning positions of TLS campaign 2008 (left); perspective view of a height coded DTM derived from the TLS data of the September 2008 campaign (right).

containing the Doren landslide. The discharge of the river varies highly. Due to the incision of the valleys, the valley slopes show bimodality in slope angles, resulting in steep slopes towards the thalweg. Consequently, settlement areas are located on the valley slopes in the upper areas. Additionally, major parts of the valley slopes, primarily the steepest ones, are covered with forest or shrubs. Fig. 2 shows an orthoimage of the study area (left) and a height coded DTM (right).

In the following, we investigate ALS data from 2003, 2006 and 2007. The mean point density varies slightly; it is approximately 2 points per square-meter. The height accuracy is about 15 cm. Additionally, two TLS campaigns were realized in 2008 and 2009. For both TLS campaigns, artificial retroreflective targets were used to support the subsequent registration process.

In September 2008, a terrestrial full-waveform scanner *Riegl LPM-321* was used. This instrument allows for a maximum measurement distance of 6 km with an accuracy of approximately 10 cm, depending on the measurement distance. Using the on-board point extraction algorithm,

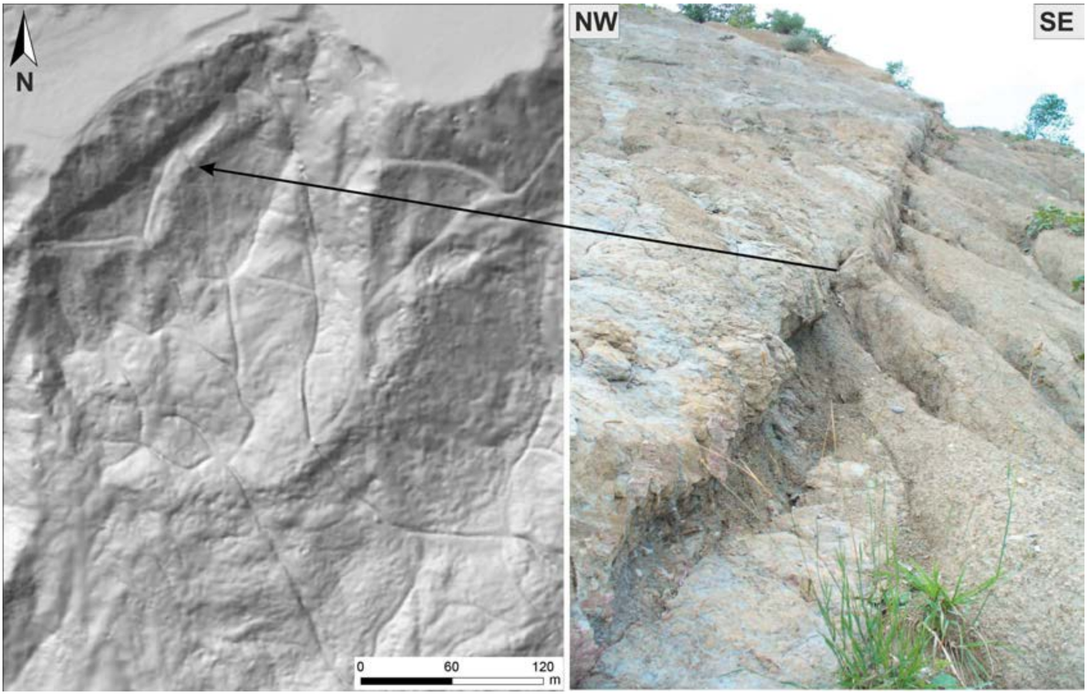

Fig. 3: Hillshade of a DTM derived from ALS-data of the year 2003 (left). A major fault observed in the field is dissecting the main scarp; black arrow shows its location on the hillshaded DTM (right). The height of the terrain scarp along the fault is approximately 50 cm.

the instrument determines up to three echoes per shot. Unfortunately, the internally sampled waveform could not be processed properly with "standard" wave-form processing approaches (e.g. [5], [14], [15]) and was therefore not used further. All together, approximately two million echoes were recorded from three scanning positions (see Fig. 2, left) resulting in a mean point density of approximately 20 cm.

In August 2009, a terrestrial scanner *Riegl LMS-Z420i* was used. This instrument records one echo per shot only. However, it enables faster sampling rates and hence higher point densities. Seven scans from five scanning positions were realized and 2.5 million points were captured.

During the TLS field campaigns the local geologic and geomorphic setting was documented, too. Structural geologic field measurements were taken close to the mass movement for characterization of the host rock. Field observations revealed a large number of cracks and faults within the interbedded marls and sandstones surrounding the landslide. Fig. 3 shows a prominent fault cutting the main scarp and its appearance in the hillshaded DTM derived from ALS data in 2003. In the area affected by the mass movement itself, orientation, length and position of cracks were recorded using GPS. These cracks were open and not filled with any kind of material. The results of the field measurements were visualized using Schmidt's net lower hemisphere plots (Fig. 4), a common technique in structural geology. The fault shown in Fig. 3 has an orientation of NNW-SSE. This is in accordance with the linear feature observed in the hillshaded DTM of 2003. Other linear features detected in the ALS and TLS data using the described processing techniques (i.e. segmentation) were verified or rejected by means of field measurements.

4. Experiment and Discussion

We applied the described segmentation approach to the ALS and TLS point clouds. The investigated region covers approximately 600 by 1,000 meters. In Fig. 5, four different parameters (i.e. slope, aspect, number of points per plane, standard deviation of plane fit) as determined for each segmentation plane are shown for a selected region of the 2007 ALS data set. This point cloud originally consisted of 700,000 points. Of that, 225 planes were determined using a distance tolerance of 50 cm and excluding small planes with less than 500 defining points. These parameters were determined

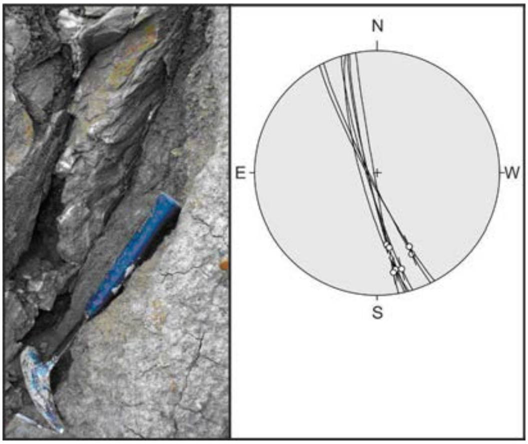

Fig. 4: Structural geologic field measurements of the faults shown in Fig. 3 indicate a NNW-SSE orientation. The field measurements were plotted using Schmidt's net plots. It is important to note that many linear features in the host rock surrounding the mass movement have similar orientation.

empirically. Decreasing the tolerances resulted in an over-segmentation with numerous very small faces and numerous points not assigned to planar structures. Increasing the tolerances led to under-segmentation or erroneous results. The local normal vector was determined from 16 points, hence the local regression plane is fitted to those 9 out of the closest 16 neighbors of each point which are most likely to represent a planar structure. The proper neighborhood-size was selected empirically by evaluating color-coded plots of the resulting normal vectors and of the local roughness which was determined from the circumscribing covariance ellipsoid.

Color coded visualizations of the respective parameters are shown in the left column. The center column shows the distribution of the parameters with respect to the number of planes and the right column with respect to the number of points. These two histograms may vary for the same parameter due to the fact that having a large segment with many points assigned to, this segment is counted only once for the "number of planes" histogram while many points with the same parameter do exist. Hence, the segment-based analysis gives the global trend (i.e., how many regions with a certain parameter are found) while the point-based analysis gives a hint to the total area if a homogeneous point distribution is given. Therefore, in order to equalize the two histograms, a normalization of the plane-based parameter considering the area covered by the plane would be necessary.

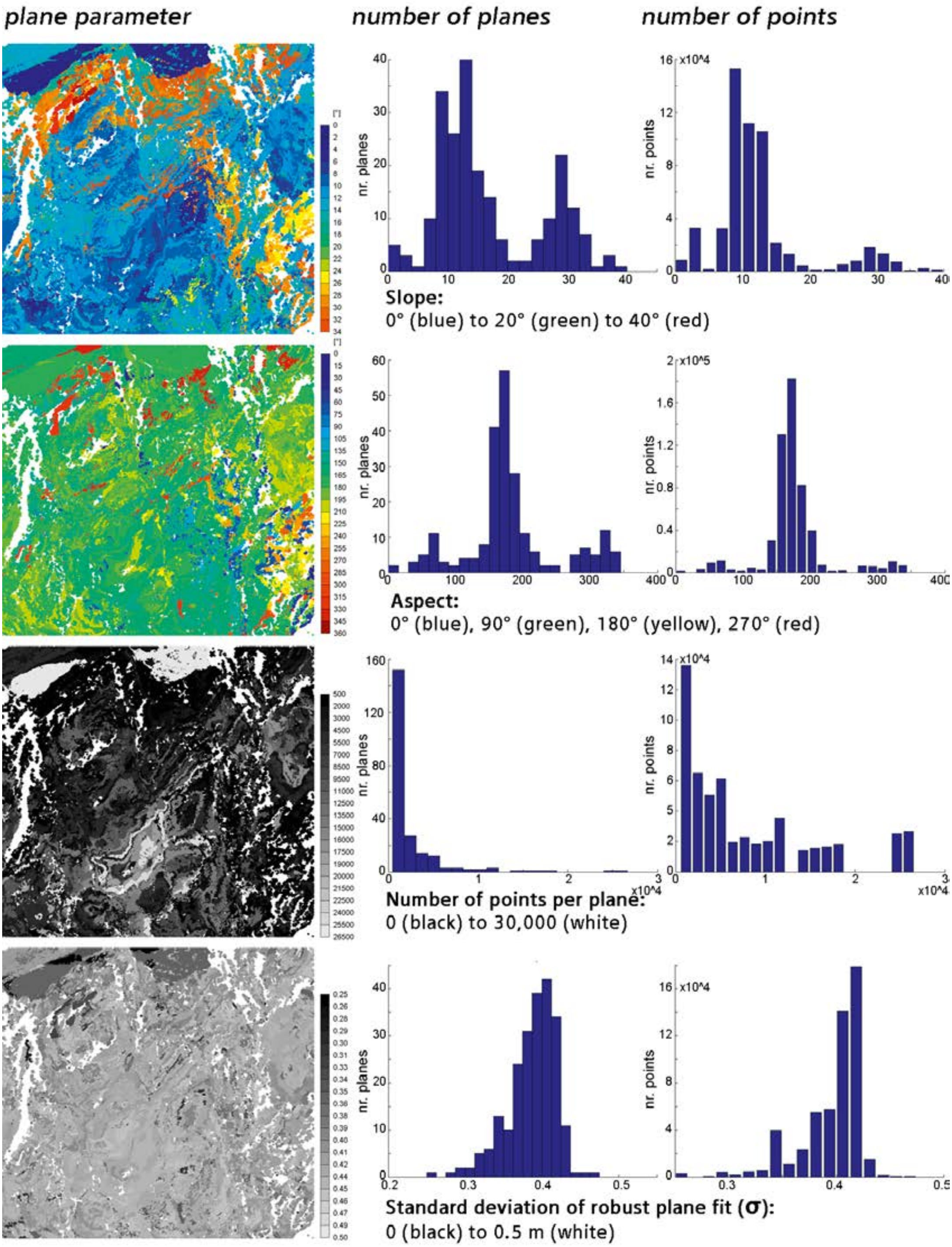

Fig. 5: Analysis of plane parameters derived from the ALS 2007 dataset. The left column shows the parameters “slope”, “aspect”, “number of points per plane”, and “standard deviation of plane fit” as determined for each plane. Color codes are indicated on the right hand side of each parameter map. The histograms show the distribution of these parameters with respect to the number of detected planes (center column) and the number of points (right column).

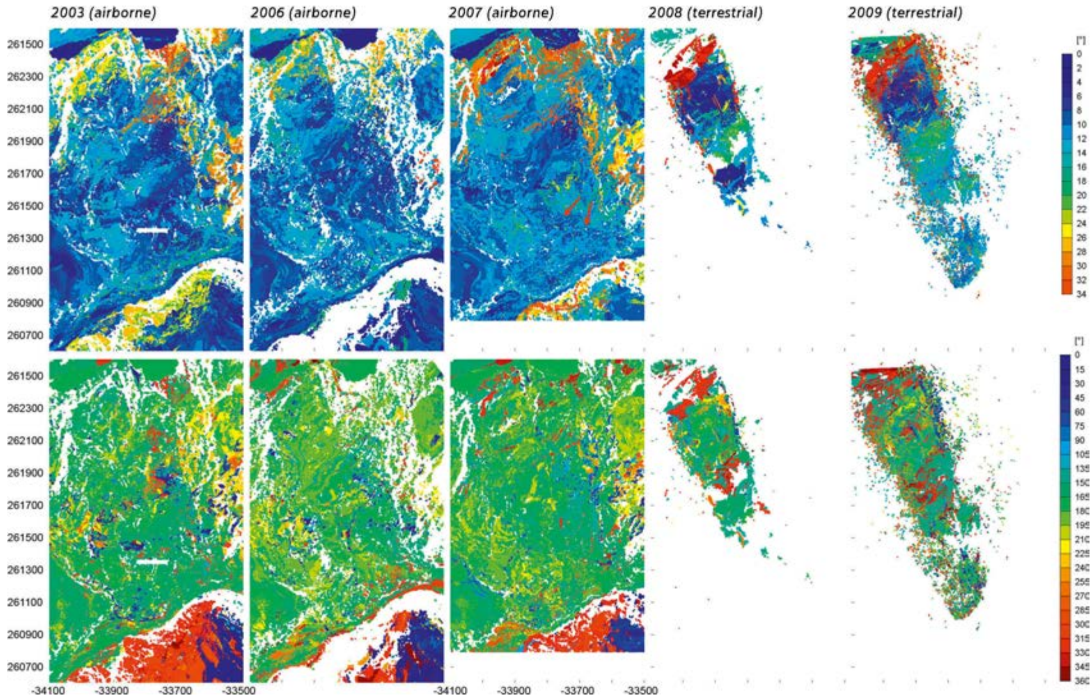

Fig. 6: Time series of the Doren landslide region from 2003 to 2009. The upper image series shows the slope angles of the fitted planes, the lower one shows their aspect angles. On both types of maps changes in the shape of the landslide can be observed. On the slope map, the progressive denudation of the main sliding plane is clearly indicated by the on-going steepening along the main scarp, whereas on the aspect map of the ALS data, the change in shape of the landslide toe can be documented.

For the two parameters slope and aspect, a time series of the five available datasets from 2003 to 2009 was generated as shown in Fig. 6. Although the amount of data was reduced approximately by a factor of 3,000, the major differences in the surface caused by the landslide can be seen clearly. Especially the increasing slope angle in the north-western region (i.e. the upper main scarp) is visible, and dynamic changes are discernible within the whole region.

For all ALS point clouds, the parameters as described above were applied. For the TLS data, the neighborhood for normal vector estimation was increased to 32 in order to cope with the higher point density and the vegetation points. Therefore, vegetation points do not influence the result significantly, although large areas of the investigated region are covered by vegetation. This is enabled by the implicit elimination of those points during the determination of planar structures. As mentioned in the theory-section, the robust estimation of the local tangential planes, allows for eliminating points representing non planar structures. A shortcoming of the current implementation of the segmentation is the fact that for large point clouds – like those presented – a connected component analysis can not be applied due to memory restrictions. Such a connected component analysis should enable separating disconnected regions with identical plane parameter. If this is not performed – as it is the case for the presented results – originally disconnected regions are assigned to the same planar structure. This has no influence on the analysis of local surface parameter like slope, aspect, or sigma. However, some of the vegetation points may be assigned to planar regions (see Fig. 6, right), especially if numerous vegetation points are in the point cloud (e.g. TLS 2009). What is clearly visible on the slope maps of Fig. 6, is the progressive denudation of the main sliding plane and thus a steady increase in slope angles.

According to field observations and the analysis of the ALS and TLS data, the landslide of Doren in its present form shows features similar to those of a complex rotational landslide as described by [16]. Material on the unstable slopes starts moving along a convex main scarp the geometry of which is influenced by

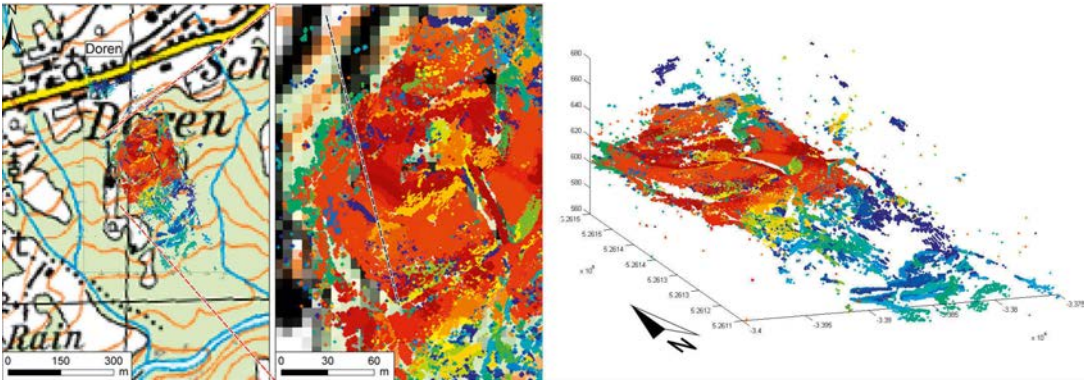

Fig. 7: *Fitted planes of the TLS data from 2008 on the background of the Austrian topographic map (BEV, ÖK 50-BMN, Blatt 112 Bezau, scale: 1:50,000). The center image is an enlargement of the overview map shown left and the right image shows a perspective view of the segmentation. Each patch with a given color represents a different plane. The best approach for the analysis of such plane-maps would be the pattern analysis of the plane boundaries. If plane margins do line up in a certain pattern, a geological or geomorphological meaning should be verified in the field. The dashed black line in the right hand image, for instance denotes the location of the fault dissecting the main scarp also shown in Fig 3. Note that some man-made structures are also outlined: these belong to the drainage system that had been initiated after the major landslide movement in 2007.*

the lithology of the host rock. The margins of the Doren landslide are sharp and reveal the host rock forming a steep slope on either side. Downwards, the convex main scarp rises underneath the gravitatively moving mass and induces the formation of a tongue-shaped landslide toe (see also: [13], [17]). The main driving force inside the mass movement is gravity. Transverse cracks form, as the material migrates down the convex main scarp and its lower rise. Accordingly, linear or planar features derived by segmentation outside the area affected by the mass movement, may show a certain pattern linked to faulting within a regional stress field with σ_1 oriented NW-SE and σ_3 oriented NE-SW ($\sigma_1 > \sigma_2 > \sigma_3$, see also: [18]). On the mass movement itself, however, a different pattern related to gravitational sliding should be dominant (e.g. transverse linear features, see [16]).

Comparing the images of the time series (Fig. 6), the main scarp is clearly visible, as well as the margins of the landslide. Other features include the transverse zones of lower slope angles within the mass movement area. What is only visible after a thorough evaluation is the fact that the main toe in the center of the landslide evolved during 2007 (as indicated by red arrows on the slope map in Fig 6). Prior to that date, an area more to the west seems to have been active. At the same time, starting in 2007, slope angles along the main scarp increase constantly up to 2009 indicating denudation and erosion on the main scarp.

From a geomorphological point of view, classic surface derivatives such as slope and aspect provide a necessary and generally good overview on the state of the studied area. However, fitted planes derived by the segmentation algorithms can deliver a higher level of detail, especially at the boundaries between planes (Fig. 6). The segmentation algorithm is able to show distance offsets of 50 cm and bigger. Due to the additional consideration of the plane parameter, even small differences between neighboring planar structures may be determined if the planes are tilted.

Analysis of the processed ALS and TLS data, along with geologic field measurements and geomorphological field observations indicate the major role of the incision of the Weißach River in creating unstable slopes. Due to its highly variable discharge (mean annual Q = 38 m^3/s, minimum annual Q = 11 m^3/s, maximum annual Q = 440 m^3/s, measured at the station at Bozenau, directly at the confluence of the Weißach with the Bregenzerach river; values derived from the homepage of the State of Vorarlberg, [19]), the evacuation of sediment from the Weißach valley occurs intermittently. Structural geologic measurements indicate the existence of deep-seated faults formed within a regional stress field. These faults are not active, but surface processes are mainly influenced by their orientation. The most recent geomorphic process identified is gravitational mass movement on the slopes and at places, where the host rock has been dissected by older faults. The area surrounding the landslide and the landslide itself are continuously evolving with occasional peak events of mass movement (e.g. 1980s and 2005).

5. Conclusions

It could be demonstrated that a topographic surface can be properly represented by a set of automatically determined planar structures for subsequent interpretation with respect to geomorphic characteristics. The amount of data was reduced up to a factor of 3,000. Additional geological in-situ measurements verified some of our findings in the sense that similar primary directions could be found that were derived from the LiDAR data. Since planar segments robustly represent the surface at a given scale, the results are typically suitable for further analysis that implies trend characteristics. The appropriate selection of input parameters is a key issue in this processing: it determines the size and character of the resulting surface facets, and how far they estimate the real surface. Higher tolerance values (i.e. a threshold on the standard deviation of the residuals) may lead to more generalized surfaces, however the experimenter should ascertain that the resulting trend surface is still geomorphologically sound, and shows the major characteristics of the original surface. If this property can be ascertained, the geomorphic-geological analysis of the trend surface becomes feasible and the resulting parameters of the planar facets can be compared to other spatial data like drainage pattern, geological layering, schistosity, structural geological features.

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