AImon5.0 - Real-time monitoring of gravitational mass movements for critical infrastructure risk management with AI-assisted 3D metrology

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Abstract

The Earth's surface is constantly changing. Climate change is altering environmental conditions - for example, more intense and prolonged precipitation is causing more frequent landslides or rockfalls. Such events do not only affect the local population but also critical infrastructure. A key tool in integrated risk management is the availability of 4D geo-information. The information is collected through continuous monitoring in near real time. The current state of the art is fixed and autonomous permanent laser scanner (PLS) systems. PLS provide huge amounts of data. In order to make PLS and 4D analysis methods available for operational use and to limit the big 4D data to the relevant information, a new interface between the information needs of the application and the 4D acquisition and analysis is required. For the first time, this will make it possible to use state-of-the-art PLS in risk monitoring and, with the help of artificial intelligence methods, to find and evaluate specific relevant events in the huge amounts of data, to follow them in continuous monitoring and to automatically identify new events. AImon5.0 is an interdisciplinary collaboration project. The expertise of all partners will be combined to close the gap between research and application. This paper presents an advanced method using permanent laser scanners. We show how we address scientific questions from an engineering geodetic point of view, as well as in the efficient extraction of essential information from large datasets. We present a conceptual approach that clearly illustrates the interfaces from data acquisition to information.

Keywords: Permanent laser scanning, Geomonitoring, Multitemporal 3D point cloud analysis, Hierarchical analysis

1 Introduction

Gravitational mass movements, including landslides and rockfalls, represent a substantial threat to public safety and critical infrastructure in numerous regions worldwide. Consequently, precise spatial and temporal data are paramount for the early warning and evaluation of risks. In recent years, permanent laser scanning systems (PLS) have proven to be a reliable technology for the continuous collection of spatially and temporally high-resolution point clouds in various fields of application (Czerwonka-Schröder, 2023). The prevailing paradigm of data acquisition has undergone a significant shift, with new challenges arising from the substantial volumes of data generated by such systems, frequently amounting to several billion measurements per day. The efficient management of this data has emerged as a crucial prerequisite for a high-quality monitoring system, involving both the immediate availability of data and the capacity to synchronise it with the analysis units responsible for decision-making. In this context, the latency between measurement and decision-making assumes paramount importance. The extraction of relevant information from large volumes of data in real time necessitates the utilisation of artificial intelligence (AI). AI-supported algorithms facilitate the automated and reliable identification of potentially critical events and the targeted forwarding of information to decision-makers. To address these challenges and exploit the potential of PLS systems, the BMBF funded research project AImon5.0 was launched. The objective of this project is to integrate contemporary AI technologies and 4D data analyses with a specific focus on making a substantial contribution to the reduction of risk through prevention and facilitating support for risk management.

2 State of the art

In recent years, research has made significant progress in the use of laser-scanned point clouds to analyse geomorphological processes. These developments include both the assurance of data quality in point clouds and the development of methods to derive accurate change information from multi-temporal data sets.

In geodesy, the focus has been on the reduction of systematic errors in measurements and the accurate registration and georeferencing of multi-temporal point clouds. The aim of these activities is to minimise false alarms and increase the reliability of detection. Czerwonka-Schröder (2023), Friedli et al. (2019), Kuschnerus et al. (2021b) and Voordendag et al. (2022), for example, have made valuable contributions to atmospheric correction and the consideration of atmospheric effects by looking at data from laser scans covering a distance of several kilometres over Alpine valleys. The work of Wujanz (2016), Friedli and Wieser (2016), and Yang and Schwieger (2023) has contributed significantly to improving the registration and georeferencing of multi-temporal scans. In addition, considerable progress has been made in the area of data analysis.

Anders et al. (2020) and Kuschnerus et al. (2021a) developed methods for object-oriented and cluster-based analysis of point clouds, which enable reliable identification and classification of dynamic processes in 4D data sets. Winiwarter et al. (2023) and Williams et al. (2019) focused on the development of methods for the analysis of multi-epoch point clouds. These methods are particularly useful for monitoring gravitational mass movements and coastal change. Raffl and Holst (2024) contributed to the engineering geodetic integration of multi-temporal point clouds in the course of an appropriate deformation analysis, thus enabling precise tracking and analysis of surface changes by means of area-measuring sensor technology.

The state of the art is progressing quickly in the field of PLS, but most research is focused on the development on the level of single components and steps of an entire PLS observation system, as outlined above (e.g., focus on the registration step). This contribution will highlight that a holistic view on all steps and their interfaces is needed to develop improved, flexible, fit-for-purpose and AI-assisted systems in the future. AImon5.0 shall thereby provide a proof of concept.

3 System Implementation

In collaboration with the associated project partners (DB Netz AG and the State Office for Geology and Mining), the *Trierer Augenscheiner* was selected as a suitable test site. The site is a geologically prominent rock formation on the Mosel River on the northern periphery of Trier (Rhineland-Palatinate, Germany). On 26 January 2023, a rockfall occurred at this site (see Fig. 1), causing approximately 135 m^3 of rock to fall and causing significant damage to the vineyard below. Due to the precarious nature of the site, the vineyard has not been fully cultivated since. The *Trierer Augenscheiner* itself is characterised by its location in the lower red sandstone with its highly faulted and fissured sandstone layers, which have a significant influence on the stability of the slope. In addition, the rock face represents a unique geological boundary between the Palaeozoic and Mesozoic eras and is therefore of inter-regional geological significance. This combination of unstable geological conditions and its exposed location along a national road and railway line predestines the site as a test area for the implementation of our real-time monitoring system for recording and analysing gravitational mass movements, as the potential for further movements has already been demonstrated prior to the start of the project.

An extensive installation of various sensors was car-

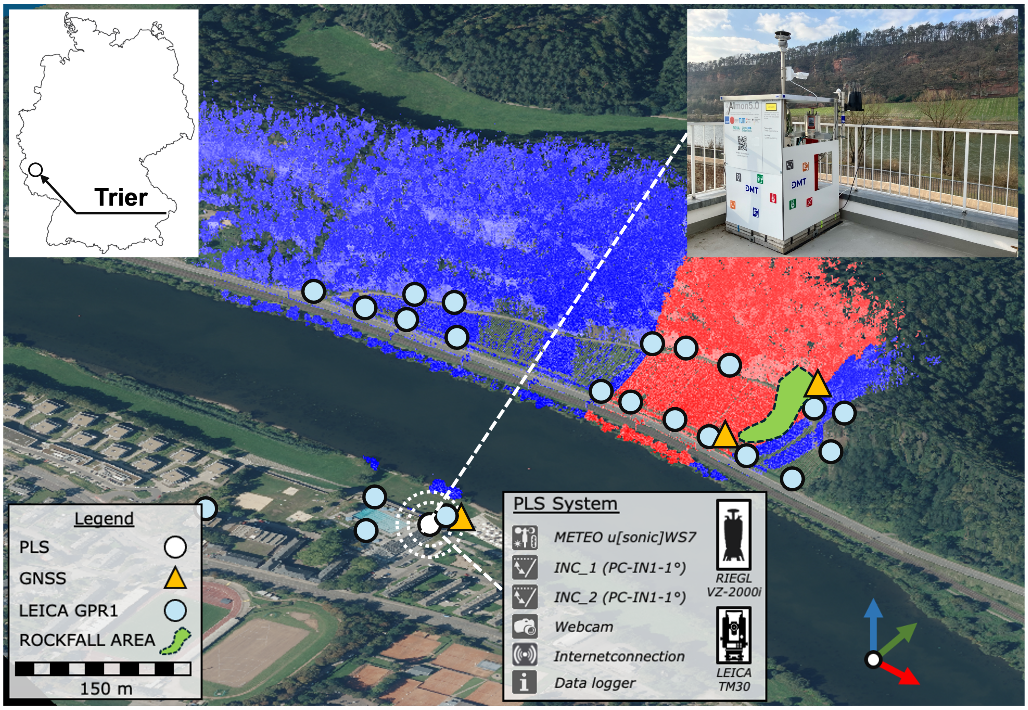

Figure 1. Three-dimensional overview of the test site at the *Trierer Augenscheiner* including applied sensor technology. (Data Source of the background map: © GeoBasis-DE / LVermGeoRP 2025).

ried out, which could be implemented on the opposite side at the municipal swimming pool facilities. From here, an average distance of approximately 250 to 300 m to the rockfall area was achieved. The monitoring system, shown in Fig. 1, consists of several sensors that not only provide continuous data on the movement of the rockfall itself, but also help to quantify systematic measurement errors in the laser scan data. The heart of the system is a RIEGL VZ-2000i laser scanner. The scanner acquires a 3D point cloud once an hour with an angular resolution of 15 mdeg (Blue Point Cloud in Fig. 1) and a detailed scan every six hours with a resolution of 5 mdeg (Red Point Cloud in Fig. 1). This data is supplemented by a LEICA TM30 total station (Schulte et al., 2025), which measures the position of 22 prisms (LEICA GPR1) on the rock itself and in the surrounding area every hour. The prisms act as reference and object points to ensure the consistency of the laser scan data. Three GNSS sensors are installed on both sides of the river. They collect daily baseline data, support precise positioning and are used to identify systematic deviations in the form of refractive effects in the electro-optical measurement across the river. In addition, two inclination sensors (POSITION CONTROL, PC-IN1-1°) monitor the stability of the survey pillars every 15 seconds to detect any changes in their alignment. A LAMBRECHT U[SONIC]WS7 weather station is installed to provide continuous data on environmental parameters such as temperature, air pressure, humidity, wind speed and global radiation that may affect measurement accuracy. A webcam provides visual insight into the terrain and weather conditions every 10 minutes. Using a remote data link, the system can be accessed online and provides relevant data to all project participants in real time.

4 Methodologies

4.1 Uncertainty reduction in the measured 4D point clouds

In order to improve the quality of the acquired laser scanning point clouds for subsequent deformation analysis, we develop effective methods to reduce the systematic uncertainties resulting from the uncalibrated instrument, atmospheric refraction, and point cloud registration.

Specifically, we develop a method tailored to the terrestrial laser scanner used to calibrate the internal deviations under controlled conditions in order to eliminate these systematic errors by suitable func-

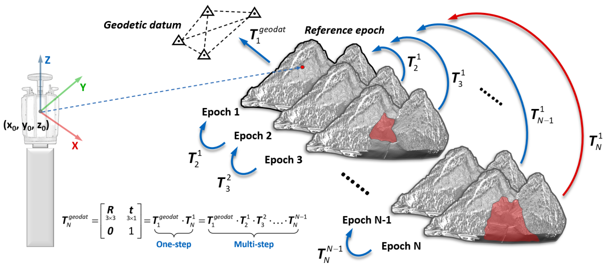

Figure 2. Workflow of robust registration of 4D point clouds from PLS (illustrated on a rockfall monitoring case).

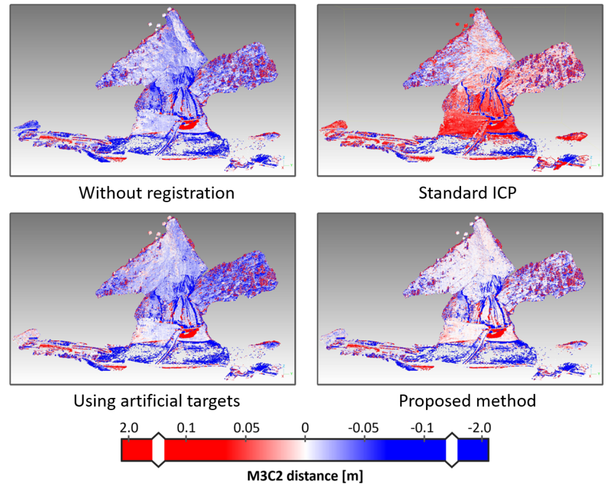

Figure 3. M3C2 distance between a registered scan and the reference epoch by different registration strategies (a test site of rockfall in Tyrol, Austria).

tions. Furthermore, we utilize approaches from Holst et al. (2018) and Medić et al. (2019) to minimize high-frequency calibration residual deviations in-situ in the field so as to achieve even higher measurement accuracy.

The systematic uncertainties caused by refraction effects and the instability of the scanner's platform can be jointly reduced by point cloud registration techniques. Detailed investigation and analysis can be found in Yang et al. (2025). As shown in Fig. 2, we first select an epoch (e.g., the first epoch) as a reference and then align all scans in the subsequent epochs with the scan in this reference epoch. Finally, these 4D point clouds can be georeferenced to a known geodetic datum. This procedure is usually performed by calculating the transformation parameters of each scan based on fixed artificial targets in the monitored scene. However, the placement of artificial targets is not cost-efficient and very challenging in some inaccessible areas. Therefore, we develop a robust target-free registration algorithm to reduce the uncertainties of measured 4D point clouds from the registration process (Yang and Schwieger, 2023). This method can automatically identify the stable areas by segmenting point clouds into small planar patches, and the stable areas are then iteratively extracted and used for an Iterative Closest Point (ICP)-based registration process. As illustrated in Fig. 2, the registration for each epoch can be performed directly to the reference epoch (i.e., in one step). If the changed areas become large and there are insufficient stable areas, we can estimate the transformation between neighboring scans and then multiply these transformation matrices to calculate the final transformation for each scan (i.e., in multi-step) (Yang et al., 2024).

To evaluate the registration accuracy of the proposed method, we calculate the M3C2 (multiscale model-to-model cloud comparison) distance on a rockfall dataset (Czerwonka-Schröder, 2023) after applying different registration strategies, including target-based method and target-free registration. Here, we assume that most of the upper parts of the rockfall surface should be stable since they are composed of rocks. From the visualized results in Fig. 3, the distance between two-epoch scans in stable areas can reach approximately 2 cm without a registration procedure. The proposed registration method shows the smallest deviations (less than 5 mm) in stable areas and thus outperforms the standard ICP and the target-based transformation.

4.2 Detection and Geometric Parameterization of Changes

In this section, we aim to extract feature points from the point cloud and track these points across successive epochs to detect possible deformations. As shown in Fig. 4, we begin by using the registered data from the previous section. We generate a digital elevation model (DEM) of the point cloud from this data, which serves as the foundation for creating a slope model. This slope model provides a suitable input for the feature extraction algorithms (Holst et al., 2021).

Our methodology is both adaptable and effective. We have identified SIFT, ORB, and KAZE as the most effective algorithms for feature extraction. In some cases, these algorithms can be combined to

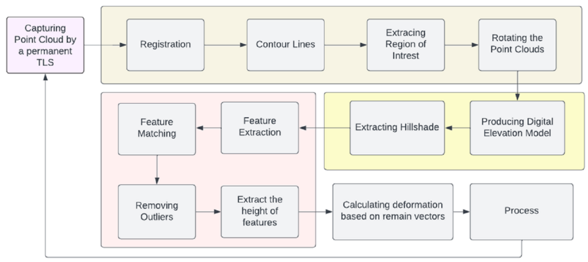

Figure 4. Flowchart of the developed feature-based algorithm (Hosseini et al., 2025).

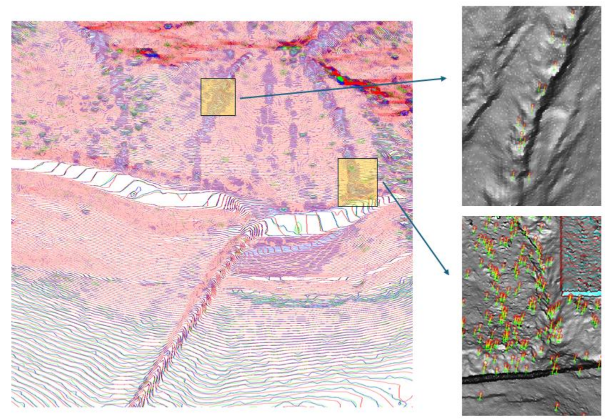

Figure 5. Extraction of deformed areas using contour lines and application of a feature-based algorithm to these areas.

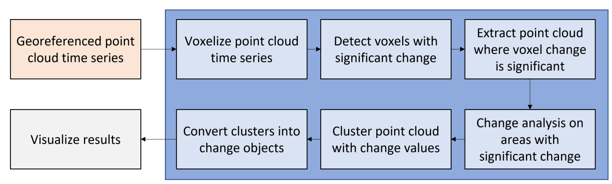

Figure 6. Flowchart of the developed method for the hierarchical analysis of surface changes in point cloud time series.

enhance accuracy. Given the large dataset, we have developed strategies to manage the high computational cost of the matching algorithms. Initially, we estimate the likely deformed regions and selectively apply the algorithms to these areas, ensuring the methodology remains applicable to various scenarios. Finally, we implement an outlier removal process to refine the results (Hosseini et al., 2023) .

Contour lines are used to visualize small-scale deformations within the target area (Hosseini et al., 2025). Based on these contours, feature extraction algorithms are applied to recognize specific features within the defined region. Once the features in each epoch are identified, the matching process begins. We can calculate the extent and direction of deformation in the area by comparing corresponding features between two registered epochs.

As illustrated in Fig. 5, contour lines delineate the deformation area. After feature extraction within this area, deformation vectors are generated. By retrieving the height of each feature from the DEM, a 3D vector field representing the deformation in the region can be constructed.

4.3 Hierarchical changes analysis

Change analysis of 3D point cloud time series is performed using voxel-based change detection and point-based change analysis methods (Fig. 6).

The method is a voxel-based algorithm for detecting surface changes. Point clouds are voxelized and examined for significant changes in the point distribution for each voxel using the open-source Python package VAPC (Tabernig et al., 2024), which is developed in the AIMon5.0 project. More specifically, the points within a voxel from two different epochs are compared using the Mahalanobis distance (Wellhausen et al., 2017), similarly to Fahle et al. (2023). Significant changes in the point distribution indicate the possibility of surface changes in the study area, thus providing a 3D mask for further, further analyses (Fig. 7). More detailed investigations on the efficiency of the surface change detection using the hierarchical workflow can be found in (Tabernig et al., 2025).

The point clouds in the masked areas are analyzed using the M3C2 algorithm (Lague et al., 2013) with the Python package py4dgeo (py4dgeo Development Core Team, 2023), which is an international open-source scientific software project. The identified changes are then spatially clustered and transformed into change events (Fig. 8) to be characterized by its spatial extent, orientation, and temporal components. Therefore, it can be used as an object to monitor changes over time. The extracted information provides insights into the current change of the area under investigation and expands the data basis for AI-supported decision-making in the context of risk assessment.

The presented hierarchical voxel-based analysis provides an effective solution for change detection

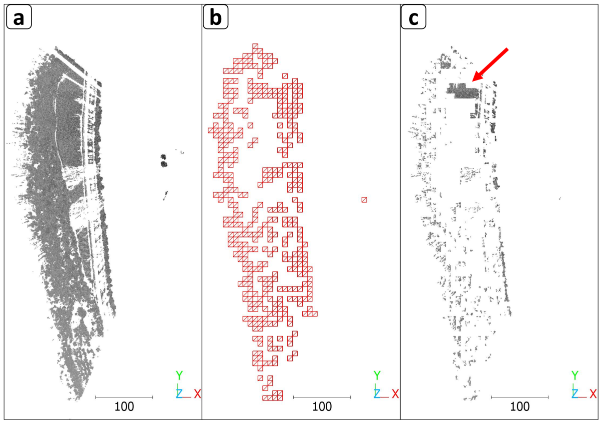

Figure 7. a) Entire input point cloud b) Voxels indicating significant change and c) Point cloud reduced to areas in which voxels show significant changes (output). The arrow points to the area in which a rockfall has occurred.

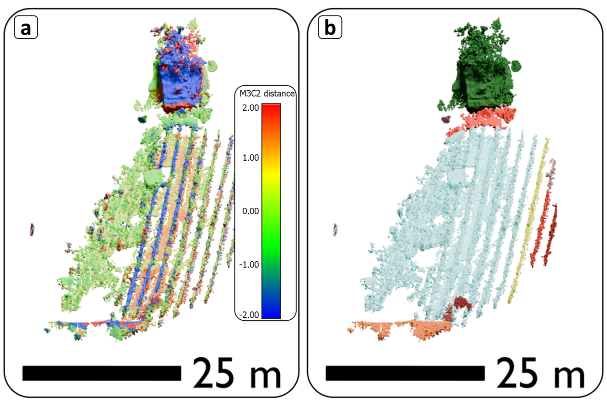

Figure 8. Result of the hierarchical analysis. a) Point cloud colored according to the M3C2 distance. b) Connected areas with change colored according to cluster ID.

in point clouds. The combination of voxel-based change detection and point cloud-based change analysis provides a comprehensive framework for change detection and classification in a hypertemporal 3D context. This framework can serve as a basis for further research and development in the field of gravitational mass movement monitoring.

4.4 Visualization of change events

The final goal is to visualize the change events extracted from the data. This aims to present the most important information to decision-makers in a compact and intuitively comprehensible way. To this end, we generate a 3D representation of the change events in the form of labeled point cloud (Fig. 8), a minimal surrounding georeferenced GIS-ready polygon, or as 3D mesh for web-based 3D visualization and volume estimation (Fig. 9).

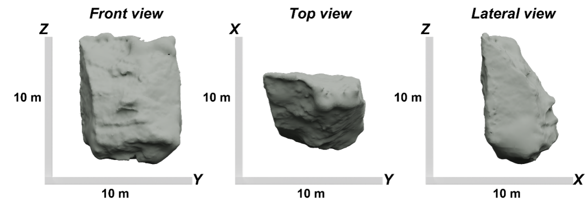

Figure 9. Mesh of the material detached during the rockfall.

Finally, we project the point cloud of the study site on the scanner view image plane (Fig. 10). Then, we project each change event on top of the image layer (Fig. 11) and create a 2D GIS layer for easy integration into common GIS software (Fig. 12).

Figure 10. Projection of point cloud in RGB raster.

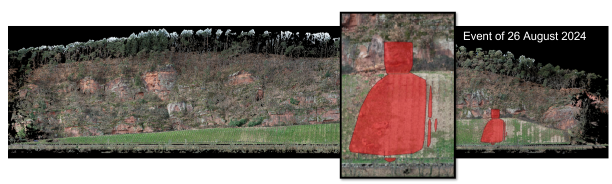

Figure 11. Change events projected onto the raster projection of the point cloud.

Figure 12. Change events converted to 2D GIS layer.

5 Results: Analysis of the rockfall event of 26 August 2024

A rockfall occurred on August 26, 2024, at the *Trierer Augenscheiner*. The event did not result in any injuries or fatalities and was recorded by our installed systems. In this section, we present preliminary results of our analysis of the rockfall event which provides an important dataset for our ongoing research. The detected changes are visualized using several approaches: point cloud visualization, projection of point clouds and the change events onto the image plane, projection of the outlines of the change events into a 2D GIS layer; and a mesh reconstruction of the release area. These visualization approaches contribute to an enhanced understanding of the rockfall characteristics.

The visualization of the point clouds of the change events is done in two ways: one based on M3C2 distance and the other based on event ID (Fig. 8). The spatial clustering of distinct change events enables the examination of change patterns within the rockfall area and facilitates event segmentation (i.e. all changes triggered by one rockfall event).

Outlines of change events on RGB image

Next, we project the outlines of the detected change events onto the image plane. This projection provides a clear visual representation of the rockfall distribution in the study area from the perspective of the PLS. Presenting the outlines in an image-based context enhances event comprehensibility and facilitates the identification of the area affected by the rockfall.

Outlines of change events as 2D GIS layer

To further visualize the change events within their surrounding context, we illustrate their outlines in a map view. This representation highlights the horizontal extent of the affected area and the relative positions of the events in an easily understandable manner. The spatial extent is readily discernible and provides valuable, interpretable information that enhances situational awareness and establishes a robust foundation for further spatial analyses.

3D mesh reconstruction of the rockfall release area

Finally, we present a 3D mesh reconstruction of the rockfall release area, created using point cloud data. The mesh illustrates the rock geometry and can be used to estimate the rockfall volume.

6 Summary and outlook

In our AImon5.0 case study, we presented the real-time monitoring of gravitational mass movements at the *Trierer Augenscheiner* using laser scanning and AI-based algorithms. Our approach enables precise detection and analysis of gravitational movements. Key methods for reducing uncertainties in 4D point clouds have been developed, which support the identification and classification of changes and significantly assist decision makers in risk management.

Our methods were successfully applied during the 26 August 2024 rockfall, demonstrating the potential of this technology. In the second year of the project, we are focusing on further developing these methods and their AI-support to achieve a high level of automation and to investigate potential indicators. There is also considerable potential to apply our methods to low-cost sensor technology to increase scalability. In addition, the developed methods will be added to the open-source py4dgeo library to make the results and tools available to the scientific community and other applications.

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