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Segment-wise ICP for Enhanced Point Cloud Registration in Low-Cost Photogrammetric Landslide Monitoring

Lukas Lucks[1], Christoph Holst[1]

[1] Chair of Engineering Geodesy, TUM School of Engineering and Design, Technical University of Munich (TUM)
80333 Munich, Germany
(lukas.lucks, christoph.holst)@tum.de

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Abstract

Accurate registration of photogrammetric point clouds is essential for reliable geometric monitoring of slope instabilities. Although low-cost imagery provides an easy and inexpensive option for data acquisition, it often suffers from doming and drift-induced errors during reconstruction, resulting in geometric distortions within the point cloud. To mitigate these effects, a method for improving point cloud registration based on an segment-wise Iterative Closest Point (ICP) algorithm is presented. The approach subdivides the point cloud into small, locally rigid segments that are each aligned individually with a reference model. To ensure smooth transitions between neighboring segments, an interpolation of the local transformations is applied. The method is evaluated using data from Mt. Hochvogel, where several video sequences of the summit area are captured with low-cost cameras. For registration and reference, terrestrial laser scanning (TLS) data and a photogrammetric point cloud from an earlier epoch are used. The latter is used for change analysis based on M3C2 distance computation. The results demonstrate that the described distortions can be substantially reduced, particularly in comparison to a single global ICP registration, providing an effective means of improving registration accuracy for low-cost photogrammetric monitoring, especially when ground control point (GCP) measurements are not feasible. The overall registration quality depends strongly on the reconstruction quality and the chosen part size. Segments that are too small may not provide sufficient spatial structure to ensure a stable ICP solution in all three dimensions, whereas larger segments limit the local adaptability.

1. Motivation

One of the most common natural hazards in mountainous regions are landslide activities such as rockfalls, debris flows or slope failures. An increase in such events is expected due to global warming and its consequences, including permafrost thaw and more frequent extreme rainfall. As modern geodetic monitoring of these processes often requires substantial equipment and time, a simple, low-cost, and readily available instrument would be advantageous for wide-area deployment.

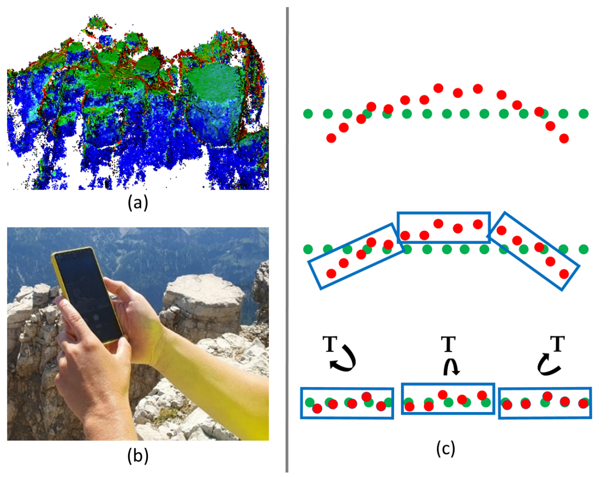

Figure 1. Change analysis (a) based on a point cloud acquired with a mobile device (b). Blue boxes indicate locally rigid transformation regions used to improve the distorted point cloud (red) by alignment with the reference model (green).

A simple, low-cost measurement system is offered by smartphone cameras, which have been demonstrated for topographic surveying and change detection of coastal cliffs (Luetzenburg et al., 2024) and landslides (Chidburee et al., 2016). For such acquired point clouds, uncertainties can cause distortions and inaccuracies. In Structure-from-Motion-based (SfM) point clouds, systematic errors often manifest as doming, caused by inaccurately estimated distortion parameters or inappropriate acquisition geometries (Sanz-Ablanedo et al., 2020) as well as drift-induced errors in sequential or incremental reconstructions (Cornelis et al., 2004, Holynski et al., 2020). For inter-epoch comparisons of point clouds, registration and scaling are required, often using ground control points (GCPs), which improve reconstruction quality and reduce uncertainties (Nesbit et al., 2022) but are time-consuming, require additional equipment, and may be impossible in inaccessible or hazardous terrain.

To address these issues, we

- present a workflow for the registration and refinement of photogrammetric point clouds in the context of landslide monitoring,
- evaluate whether, and to what extent, low-cost imagery can be employed for monitoring rock-slope failures, and
- investigate whether potential point-cloud distortions can be mitigated to enhance registration accuracy.

The main idea of the workflow is illustrated in Figure 1. The acquired point cloud (red) is distorted and displaced with respect to the reference model (green). By assuming locally rigid areas, locally valid transformations can be derived for individual segments of the point cloud, aligning the points with the reference model.

The concept of exploiting local consistency within point clouds to improve reconstruction quality has been addressed in several studies. In a patch-based registration approach, locally stable regions are identified and used to derive a more reliable alignment (Yang and Holst, 2025). Other works focus on enhancing reconstruction already during camera pose estimation. Chen et al. (Chen et al., 2023) proposed a coarse-to-fine incremental SfM strategy that combines global constraints with locally refined optimization and integrates additional sensors such as inertial measurement units (IMUs). Similar concepts are implemented in multi-camera systems, where relative camera positions are incorporated as additional constraints within an incremental SfM framework (Cui et al., 2023). Known 3D models in the form of LiDAR maps have been used to establish image-to-point-cloud correspondences, thereby achieving drift-free reconstructions (Bai et al., 2024).

Low-cost sensors have also been applied to geospatial monitoring tasks in recent years. Smartphones equipped with LiDAR scanners (Antón et al., 2025, Luetzenburg et al., 2024) or used in combination with external GNSS-RTK rovers (Zollini and Marconi, 2025) have proven capable of producing accurate topographic models. In addition, multi-image monitoring systems such as multi-smartphone setups (Fang et al., 2022) or fixed camera installations (Bruno et al., 2020) have been employed for detecting rockfall events (Blanch et al., 2024) and tracking landslide activity (Khan et al., 2021). In addition to terrestrial applications, low-cost UAV-mounted cameras have been employed in various studies for geomorphic monitoring and change detection (Cirillo et al., 2024, Yordanov et al., 2023).

In this work, an segment-wise registration method for photogrammetric point clouds derived from video sequences is presented. The approach is evaluated using data from the Mt. Hochvogel site in the Alps (Germany). The quality of the resulting point clouds and their registration is evaluated using terrestrial laser scanning (TLS) data, and the registered models are subsequently used for change analysis based on point-cloud comparisons.

2. Method

The proposed workflow (Figure 2) adapts existing approaches (Dehbi et al., 2019, Lucks et al., 2021), originally developed to improve the trajectories of multi-sensor systems in urban environments. The input data consist of a photogrammetric point cloud and the corresponding camera positions, which are prealigned using either a coarse global ICP registration or manually selected feature points. In the context of landslide monitoring, the reference model represents a registered and geometrically consistent point cloud. This model also includes information on stable and unstable regions, allowing the selection of suitable regions for the registration process. Because of the prealignment, this information can easily be transferred to the input data, enabling the partitioning of the point cloud into stable and unstable regions.

The point clouds are divided into individual segments, which are assumed to be locally rigid. These segments are defined by a centerline derived from the shape of the reference model. To achieve this, the points are sorted along the first principal axis,

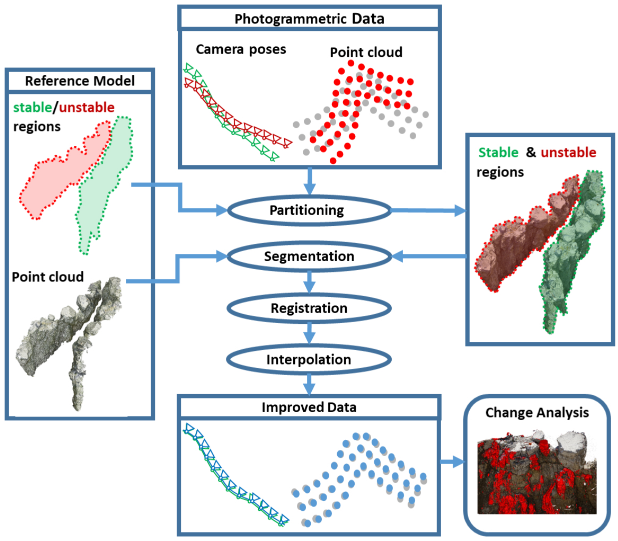

Figure 2. SegICP workflow for photogrammetric point cloud registration, including partitioning into stable and unstable areas, segmentation into locally rigid areas, alignment with a reference model, and smoothing by interpolation between neighboring segments.

and local centroids of the point cloud are determined using a moving average. By specifying a fixed length along this line, segment boundaries can be defined that adapt to the geometry of the point cloud. Based on these boundaries, both the model points and the photogrammetric points are assigned to their respective segments. An segment-wise ICP (SegICP) registration is then carried out between the model and the input point cloud. The resulting transformations are applied to both the stable and unstable regions of the point cloud as well as to the camera trajectory points. To obtain a smooth overall result, each point is registered by weighted averaging between the two nearest transformations. As a result, both an improved trajectory and an improved point cloud are obtained.

These outputs serve as the basis for the subsequent change analysis. For this purpose, multiscale model-to-model cloud comparison (M3C2) distances (Lague et al., 2013) are employed to detect spatiotemporal deformation patterns between epochs. A distinction is made between sudden changes caused by the removal of material, such as rockfall events, and gradual deformations of otherwise rigid areas. The former are identified using a threshold greater than 0.2 m and are excluded from the subsequent deformation analysis.

3. Datasets

The proposed approach is evaluated and applied to datasets acquired at Mt. Hochvogel, a well-studied and currently active rock-slope failure in the Alps (Raffl and Holst, 2025, Leinauer, 2024). The site is characterized by a large crevice that divides the summit into a stable and an unstable part. The sidewalls of this crevice are monitored to obtain information about the overall deformation of the slope and the progressive movement of the unstable rock mass (Lucks et al., 2024).

In this study, different cameras were employed to record video sequences along the study area (Table 1). The first camera (Cam 0) corresponds to a professional full-frame digital camera, which provides high-resolution imagery and serves as ref-

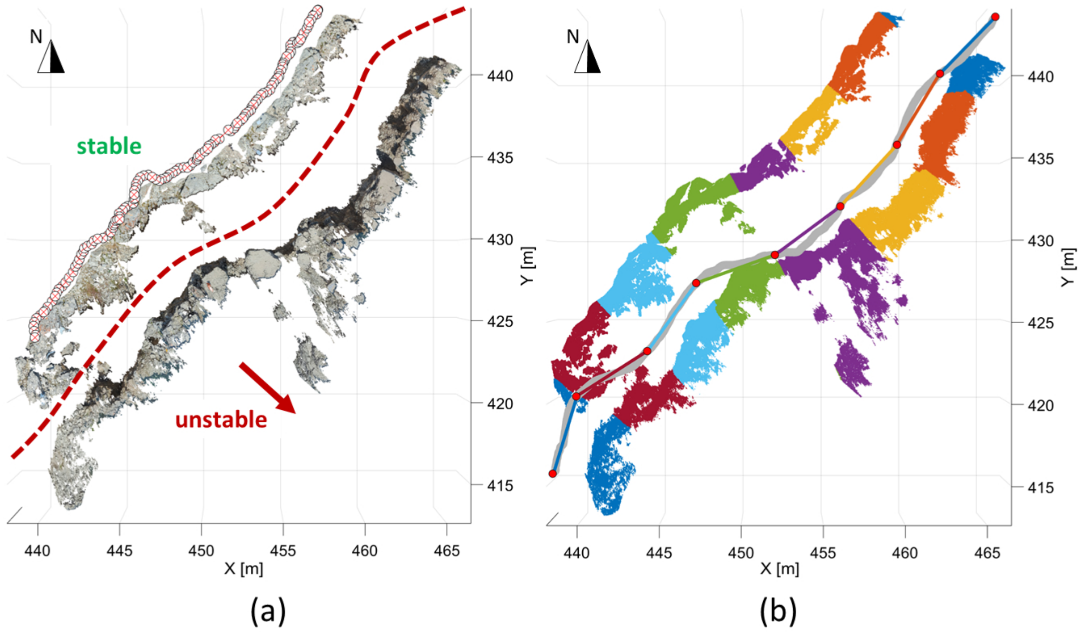

Figure 3. Top view of one of the captured point clouds of the summit (left). The approximate course of the crevice is shown as a dashed red line, and the main movement of the unstable part is indicated by a red arrow. The camera positions on the stable side are represented by crossed circles. The corresponding segmentation of the point cloud into eight segments is shown as an example on the right. Points of the same color belong to the same part. The individual segments are defined along the length of the centerline (gray line) and are marked by red endpoints.

name	model	size [px]	GCPs	images
Cam 0	Sony Alpha RII	7952×5304	14	78
Cam 1	Nikon W100	1080×1920	12	503
Cam 2	Samsung Galaxy S10	1080×1920	11	319

Table 1. Overview of the captured datasets.

erence data. This setup has previously been demonstrated in rock-slope monitoring applications (Lucks et al., 2021). The second and third datasets (Cam 1 and Cam 2) were acquired using low-cost consumer devices, including a compact camera with a small image sensor and a mobile smartphone equipped with fixed-lens optics.

An overview of the captured data at the test site is provided in Figure 3a, showing a point cloud of the stable and unstable regions of the summit together with the trajectories of the recorded video sequences. The images and videos were captured from the stable area, with the viewing direction oriented towards the unstable part, so that parts of both regions are visible in most frames (Lucks et al., 2021).

For each dataset, a three-dimensional reconstruction was performed using the photogrammetric software Pix4Dmapper, generating a dense point cloud and estimating the corresponding camera trajectories. To evaluate the proposed registration approach, the processing was conducted twice — once without and once with Ground Control Points (GCPs). The reconstruction without GCPs serves as the input for the presented registration method. The GCPs were measured by means of total station surveying.

As a reference model for the registration, a TLS point cloud is used, which was acquired using a Leica RTC360 laser scanner in 2024 from approximately 12 scan positions, providing an average point spacing of approximately 3 mm at 10 m distance. To assess the impact of the registration on the subsequent change analysis, a photogrammetric point cloud acquired in 2021 is used (Lucks et al., 2021). This dataset is obtained from photogrammetric measurements and exhibits a comparable quality to the TLS point cloud (Raffl et al., 2025).

4. Results and discussion

Segmentation To evaluate the quality of the SegICP registration, the correlation between the registered and the reference TLS point cloud is analyzed. For this purpose, the point cloud is divided into individual segments based on its centerline. An example result for the point cloud of Cam 2 is shown in Figure 3b, illustrating the segmentation into eight segments. A visual inspection reveals that, due to the linear shape of the study area, the resulting segments are approximately equal in size. Slightly smaller segments appear at the beginning and end of the area, as the centerline is estimated from the TLS point cloud and extends slightly beyond the area covered by the camera-based point clouds.

Registration Based on the described method, the point clouds of all cameras are registered. The registration quality is evaluated using the M3C2 distances to the reference TLS point cloud. These distances are calculated not only for the SegICP registration but also for the initial point clouds that are registered globally using ICP, as well as for the GCP-based registration. The results for the configuration with four segments are presented in Figure 4 (blue: GCP-based, yellow: global ICP, orange: SegICP). When analyzing the results of Cam 0, it becomes evident that the segment-wise registration does not provide any improvement. The mean distance is approximately 2 mm larger

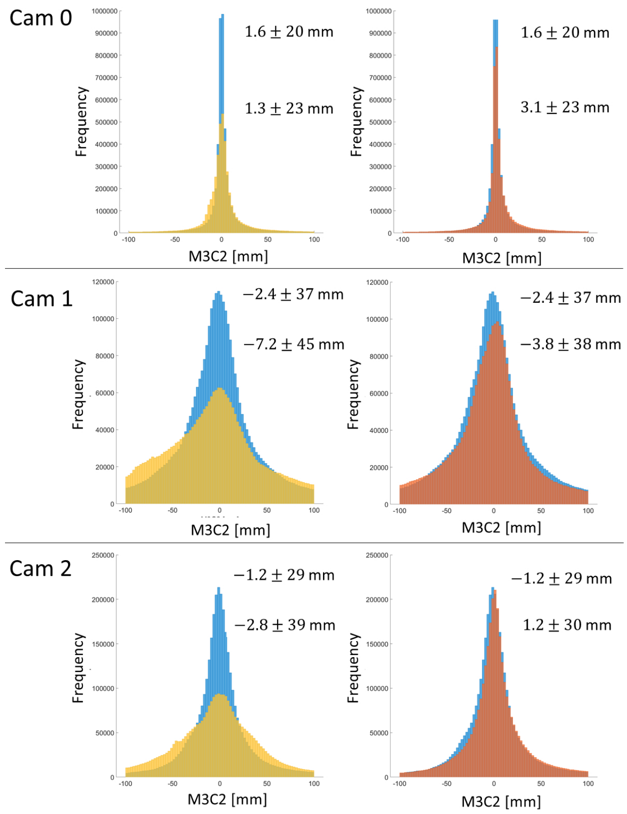

Figure 4. Histogram of M3C2 distances between the TLS point cloud and the global ICP (yellow), SegICP (orange), and GCP-based (blue) registrations. The mean and standard deviation of each dataset are shown next to the corresponding histogram.

compared to the other two registration approaches. The GCP-based and global ICP registrations yield comparable results. This indicates that the high image resolution and the absence of motion blur during image acquisition result in a precise point cloud without noticeable drift, rendering the SegICP registration unnecessary.

A different behavior is observed for the other two cameras. For both datasets, the mean distance as well as the overall scatter can be significantly reduced by the SegICP registration, particularly in comparison to the global ICP solution. The registration using GCPs performs slightly better for Cam 1, while for Cam 2 the results are almost equivalent.

The results derived from the histograms can also be verified visually based on the M3C2 distance maps of the point clouds (Figure 5). When examining the M3C2 distances of the ICP registration of Cam 1, it becomes evident that the point cloud is not free of curvature. The color distribution follows a nearly symmetric pattern, characterized by large distances at the edges, areas with approximately zero distances in between, and large distances in the center. Through the SegICP registration, this pattern is largely reduced, although some isolated areas with higher deviations (greater than 0.1 m) remain visible. These local deviations are likely related to reconstruction errors caused by unfavorable lighting conditions inside the crevice, a greater distance from the camera positions, or low and ambiguous surface texture. To a smaller extent, such regions of higher deviation also occur in the GCP-based registration. A similar pattern is observed for Cam 2, although the overall distances are considerably smaller.

Number of Segments The quality of the point cloud depends on the number of segments into which it is divided. Figure 6a shows the mean distance to the TLS reference point cloud for the individual cameras as a function of the number of segments. A higher number of segments (smaller segment length) leads to a slight decrease in the mean distance.

Uncertainty in the registration is influenced either by poor spatial coverage of the point cloud in three dimensions or by the local quality of the reconstructed points (e.g., unfavorable illumination or matching errors). As long as sufficient spatial structure is available for an unambiguous registration, smaller segments enable a better local adjustment and consequently lower deviations. In general, the distances are largest for Cam 1 and smallest for Cam 2, while the influence of the registration for Cam 0 remains nearly constant.

Change Analysis In the previous analyses, the entire point cloud is used for registration, since all datasets originate from the same epoch. However, this is not possible for change analysis due to the occurrence of surface movements within the point cloud. In the presented case, this means that only the points of the stable part can be used (Figure 3a), which results in a significantly smaller number of points and a much lower spatial coverage. The stable area mainly consists of flat surfaces with a few single boulders and outstanding rock structures, but lacks pronounced height variations such as those along the sidewall of the crevice. The effects on the registration results are shown in Figure 6b, again as a function of the number of segments. The results show that the overall mean distances increase, reaching up to approximately 16 mm for Cam 1 compared to 4 mm before, and approximately 5 mm for Cam 2 compared to 1.5 mm.

The point cloud registered using the stable area are compared to a point cloud from a previous epoch. The histograms in Figure 7 present the M3C2 distances of the unstable region of the summit. As a reference, the TLS point cloud from 2024 is compared with the photogrammetric point cloud from 2021, resulting in the histogram shown in the figure. It shows two distinct peaks at -54 mm and -9 mm. Together with the displacement pattern shown in Figure 8, this indicates a block-wise movement of the entire summit area (Lucks et al., 2024). The larger peak corresponds to the vertically oriented sidewalls, while the smaller peak represents the horizontal surfaces, resulting in an almost horizontal movement of the unstable part toward the valley.

When comparing the histograms (Figure 7) and displacement patterns (Figure 8) derived from the point clouds of Cam 1 and Cam 2, clear differences in the registration quality become apparent. Both datasets show the two characteristic peaks of the reference histogram, although they appear slightly shifted. For Cam 1, the peaks are located at approximately –69 mm and –3 mm, with the first peak exhibiting a wider spread, indicating higher variability in the measured displacements. Cam 2, on the other hand, shows two distinct peaks at around –58 mm and 6 mm, which are considerably closer to the reference and therefore better reflect the actual motion pattern.

These results are consistent with the visual analysis shown in Figure 8. While Cam 1 demonstrates that curvature effects in the global ICP registration can be reduced through the SegICP registration (visible as smaller deviations at the model edges),

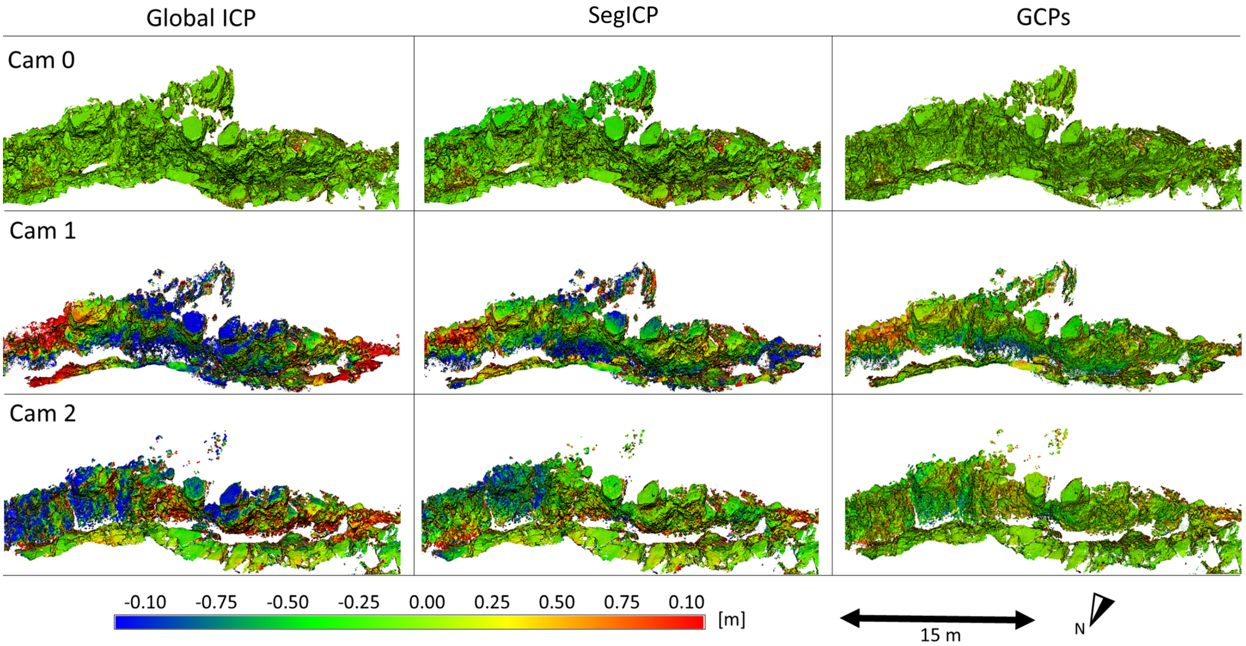

Figure 5. M3C2 distances between the TLS point cloud and the point clouds aligned using global ICP, SegICP, and GCP-based registration for the three cameras.

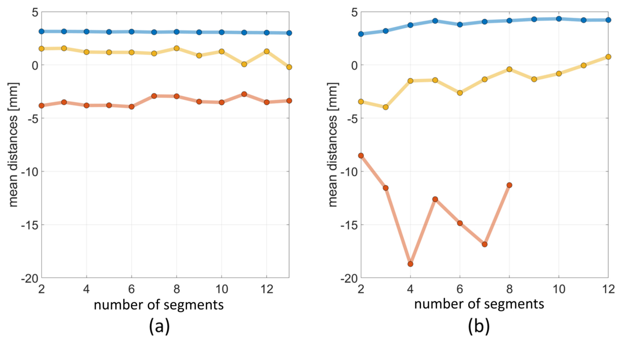

Figure 6. Mean M3C2 distances for Cam 0 (blue), Cam 1 (yellow), and Cam 2 (orange), computed for the entire point cloud (left) and for the stable part only (right).

the overall displacement pattern remains less distinguishable. For Cam 2, the improvement achieved by the SegICP is more pronounced, revealing a motion pattern that is very similar to the reference. Minor differences still exist, particularly in the left part of the study area, which is likely reconstructed with lower accuracy or provides less distinctive geometry within the stable region, making precise registration more challenging.

5. Conclusion and outlook

The SegICP approach significantly improves the registration quality for low-cost camera data compared to global ICP registration, provided that temporally and spatially relevant uncertainties are present within the point clouds. Existing offsets and scale differences can be corrected effectively. The applicability of the method, however, strongly depends on the size of the segments and the spatial extent and reconstruction quality of the point clouds, which become limiting factors in the context of change analysis—particularly when small-scale movements in the range of only a few centimeters are to be detected.

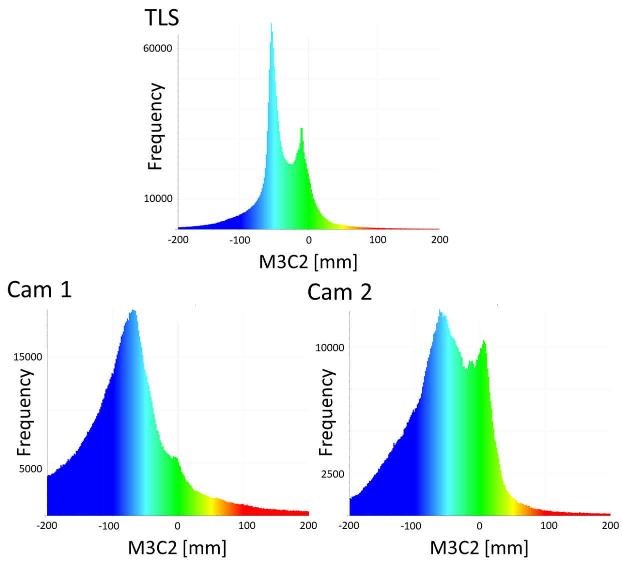

Figure 7. M3C2 distances between point clouds from 2024 (TLS reference, Cam 1, and Cam 2) and 2021.

Small-scale deviations that already arise during the reconstruction process cannot be corrected. Moreover, the selection of the segment size remains challenging when no reliable reference data are available for evaluation.

For high-resolution imagery, such as that obtained from professional cameras, these error effects do not occur to the same extent, and the SegICP registration provides no measurable improvement compared to the global ICP or GCP-based solutions. The integration of GCPs improves both the registration accuracy and the overall quality of the reconstructed point clouds. GCP-based solutions show no curvature effects and generally outperform the SegICP results.

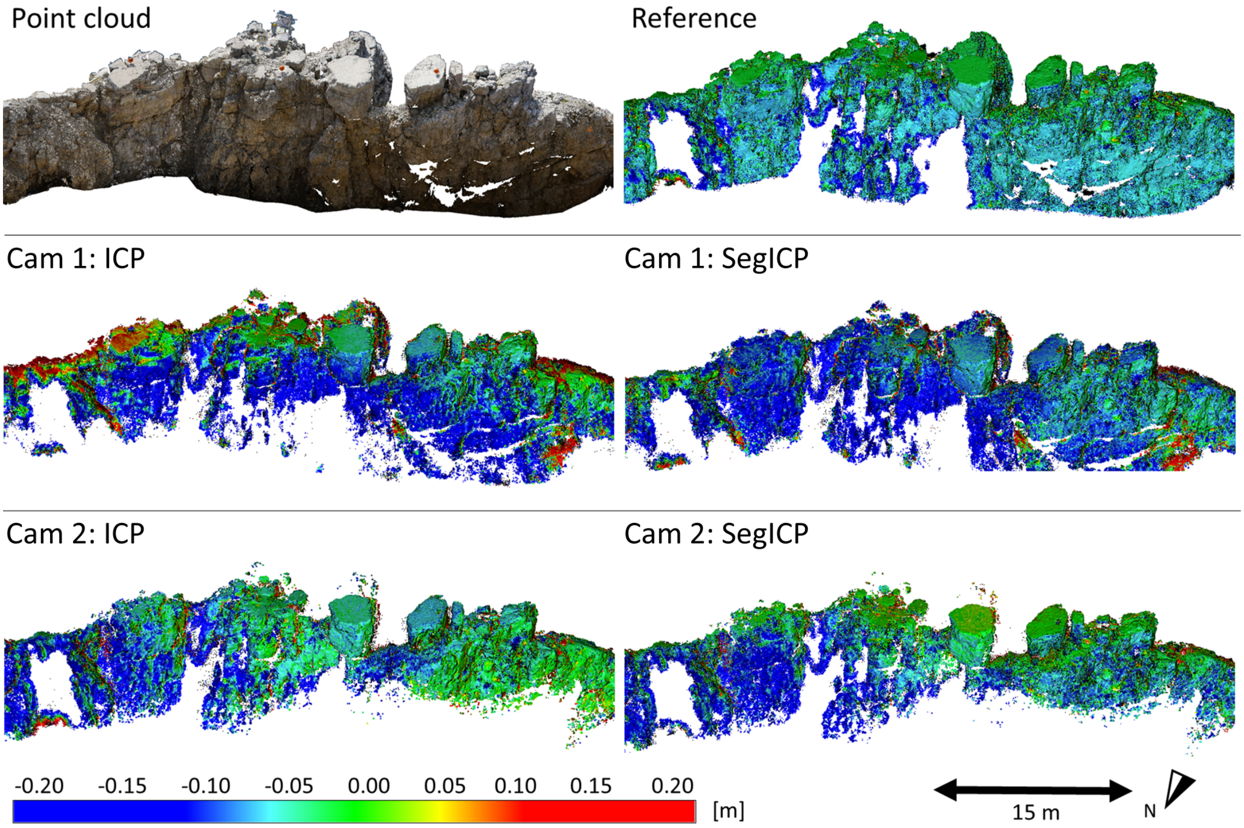

Figure 8. Motion patterns derived from M3C2 distances between the point clouds acquired in 2024 (TLS, Cam 1, and Cam 2) and the point cloud from 2021, shown for both global ICP and SegICP registration. The color scheme corresponds to that used in the histograms in Figure 7.

Future work could focus on extending and refining the presented approach. A potential extension could include a spatial analysis of surface characteristics of each segment, for example by evaluating the distribution of local normals (Raffl and Holst, 2025). Furthermore, the SegICP registration improves not only the quality of the point clouds but also the accuracy of the estimated camera positions, providing benefits for feature-based motion tracking. Currently, all points from the stable area are used for registration. However, small deviations may still occur in regions composed of debris or loose material. Identifying such areas and incorporating this information into the registration process represents a promising direction for future research.

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