EGU24-5674, updated on 14 Jul 2024
https://doi.org/10.5194/egusphere-egu24-5674
EGU General Assembly 2024

Piecewise-ICP: Efficient Registration of 4D Point Clouds for Geodetic Monitoring

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The permanent terrestrial laser scanning (PLS) system has opened the possibilities for efficient data acquisition with high-temporal and spatial resolution, thus allowing for improved capture and analyses of complex geomorphological changes on the Earth's surface. Accurate georeferencing of generated four-dimensional point clouds (4DPC) from PLS is the prerequisite of the following change analysis. Due to the massive data volume and potential changes between scans, however, efficient, robust, and automatic georeferencing of 4DPC remains challenging, especially in scenarios lacking signalized and reliable targets. This georeferencing procedure can be typically realized by designating a reference epoch and registering all other scans to this epoch. Addressing the challenges in targetless registration of topographic 4DPC, we propose a simple and efficient registration method called Piecewise-ICP, which first segments point clouds into piecewise patches and aligns them in a piecewise manner.

Assuming the stable areas on monitored surfaces are locally planar, supervoxel-based segmentation is employed to generate small planes from adjacent point clouds. These planes are then refined and classified by comparing defined correspondence distances to a monotonically decreasing distance threshold, thus progressively eliminating unstable planes in an efficient iterative process as well as preventing local minimization in the ICP process. Finally, point-to-plane ICP is performed on the centroids of the remaining stable planes. We introduce the level of detection in change analysis to determine the minimum distance threshold, which mitigates the influence of outliers and deformed areas on registration accuracy. Besides, the spatial distribution of empirical registration uncertainties on registered point clouds is derived based on the variance-covariance propagation law.

Our registration method is demonstrated on two datasets: (1) Synthetic point cloud time series with defined changes and transformation parameters, and (2) a 4DPC dataset from a PLS system installed in the Vals Valley (Tyrol, Austria) for monitoring a rockfall. The experimental results show that the proposed algorithm exhibits higher registration accuracy compared to the existing robust ICP variants. The real-time capability of Piecewise-ICP is significantly improved owing to the centroid-based point-to-plane ICP and the efficient iteration process.