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基于稳定岩石特征的无控制匹配

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摘　要

针对传统点云配准方法在复杂地质环境中控制点难以布设的问题，本文提出了一种基于稳定岩石特征作为控制点的方法。利用点云的局部几何特征与反射特征提取稳定岩石的点云面片，通过提取岩石区域表面的特征点进行特征匹配，实现粗配准。利用点到面的迭代最近点算法，实现精配准。实验结果表明，该方法能够有效降低因地质环境形变导致的配准误差，对提升形变监测精度与变形分析结果具有重要的理论意义与应用价值。

关键词

点云配准；无控制匹配；特征提取； ICP算法

Control-Free Matching Based on Stable Rock Features

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Abstract

To overcome the difficulty of deploying control points in complex geological environments, this paper presents a point cloud registration method using stable rock features as constraints. Stable rock patches are extracted based on local geometric and reflectance attributes. Coarse registration is performed via feature point matching on rock surfaces, followed by fine registration using the point-to-plane ICP algorithm. Experimental results indicate that this method effectively reduces registration errors induced by geological deformation, offering significant theoretical and practical value for improving deformation monitoring accuracy and analysis.

Keywords

Point Cloud Registration; Control-Free Matching; Feature Extraction; ICP Algorithm

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1. Introduction

Traditional point cloud registration methods typically rely on the manual placement of high-reflectance targets or ground control points within the monitoring area[1]. However, in complex geological settings such as high and steep slopes, the installation and long-term maintenance of such targets are not only logistically challenging and hazardous but also prone to displacement due to localized slope movement or surface erosion[2]. Consequently, the long-term absolute stability of these benchmarks cannot be guaranteed[3]. Moreover, steep slope surfaces are often covered by unstable features such as vegetation and loose debris, whose morphology and spatial positions can vary significantly across multi-temporal point clouds under natural environmental influences[4]. This local surface inconsistency tends to cause conventional global registration algorithms to converge to local optima, posing a major challenge for high-precision, control-free point cloud registration[5].

To address the aforementioned issues, this chapter proposes an ICP matching method based on stable rock surface features. In geological environments, deep-rooted bedrock or large expanses of fixed, exposed rock masses typically exhibit extremely high physical and mechanical stability. By extracting these invariant exposed rock surfaces and employing them as natural targets, the need for artificial control points can be effectively replaced, thereby establishing a robust spatial registration datum.

2. Methods

2.1. Extraction of Point Cloud Patches

This paper constructs a multi-source feature space based on geometric morphology and radiometric intensity to analyze the distribution patterns of different ground objects in terms of point cloud attributes, thereby separating stable rock point clouds from unstable ones[6].

（1）Eigenvalue-Based Geometric Feature Extraction

Surface Roughness: Expressed as the deviation of a point from its local neighborhood fitting plane. Stable rock surfaces exhibit macroscopic continuity while retaining certain structural textures at the microscopic scale; their roughness typically falls within a specific low-to-medium value range. Surface Curvature: Describes the degree of local surface bending. Linearity and Planarity: Exposed bedrock surfaces generally possess strong planar characteristics. By analyzing the anisotropy features of the point cloud, residual vegetation with randomly scattered spatial distributions can be preliminarily excluded.

（2）Reflectance Intensity Feature Analysis

Point cloud reflectance intensity directly reflects the reflective properties of ground objects to the laser signal and is closely correlated with material composition, surface roughness, and moisture content. In steep slope environments, significant differences exist between rock surfaces and the overlying soil or vegetation. This characteristic provides a critical basis for rapidly separating rock points from other

surface features.

The integration of multi-source constraints combining geometric and radiometric features not only effectively improves the identification accuracy of stable rock surfaces but also enhances the robustness of the algorithm to data acquired under varying environmental conditions, thereby establishing a solid data foundation for subsequent rock segmentation and fine registration.

2.2. Coarse Registration

In this study, the Sample Consensus Initial Alignment (SAC-IA) algorithm is employed to perform random sampling verification in the feature space, which effectively circumvents local optimum traps and yields a robust initial transformation matrix[7]. The specific procedure is outlined as follows:

（1）Sample Selection: Several key points are randomly selected from the source point cloud. To ensure geometric representativeness, the selected point pairs must satisfy a minimum distance constraint, thereby preventing excessive sample concentration.

（2）Feature Matching: For each selected sample point, the closest point in the target point cloud is identified via KD-tree nearest neighbor search based on Fast Point Feature Histogram (FPFH) distance, establishing corresponding point pairs.

（3）Transformation Estimation: Based on the current corresponding point pairs, an initial rotation matrix and translation vector are computed using Singular Value Decomposition (SVD).

（4）Error Evaluation: The computed transformation parameters are applied to the entire point cloud, and the global alignment error is assessed using the Huber penalty function. The Huber function mitigates the influence of large-error matches on the overall evaluation, thereby enhancing the algorithm's robustness to noise.

Following the initial alignment achieved via SAC-IA, the two epochs of steep slope point clouds, originally distributed discretely in space, attain macroscopic overlap, with large-scale features such as rock surfaces and fissures being substantially aligned.

2.3. Precise Registration

Following the coarse registration described in the previous section, the multi-temporal steep slope point clouds have achieved macroscopic spatial alignment, with rotational and translational deviations constrained within a relatively small range[8]. The conventional point-to-point Iterative Closest Point (ICP) algorithm is highly susceptible to tangential sliding errors on smooth rock surfaces. Therefore, this study introduces the point-to-plane ICP algorithm, which constrains the iterative direction using the local normal information of the reference rock surfaces to achieve precise alignment.

（1）Objective Function Formulation: The core principle of the point-to-plane ICP algorithm is to minimize the projected distance from points in the source point cloud to the local tangent planes of their corresponding points in the target point cloud.

（2）Linear Approximation of the Nonlinear Model: Solving the objective function essentially involves determining the optimal spatial transformation parameters. Since the rotation matrix R inherently contains nonlinear trigonometric functions, direct partial derivative-based nonlinear optimization is prone to converging to local optima and incurs substantial computational cost.

（3）Iterative Solution and Convergence: By constructing the normal equations, the optimal parameter increments for the current iteration are directly obtained via Singular Value Decomposition (SVD). After applying the updated transformation matrix to the source point cloud, the nearest neighbor correspondences are re-established and the normal vectors are recomputed, and the above process is executed iteratively until convergence is achieved.

3. Experiments and Results

To validate the effectiveness of the proposed algorithm, registration performance is evaluated using real-world point cloud data. Three commonly adopted metrics are employed as evaluation criteria: rotation error, translation error, and registration time. These three metrics assess registration performance from two perspectives—accuracy and efficiency—with smaller values indicating superior performance in all cases. The rotation error and translation error* are calculated as follows:

$$e_R = \frac{1}{M}\sum_{i=1}^{M} \left\| R_{m,i} - R_{g,i}^{T} \right\|_F \quad (1)$$

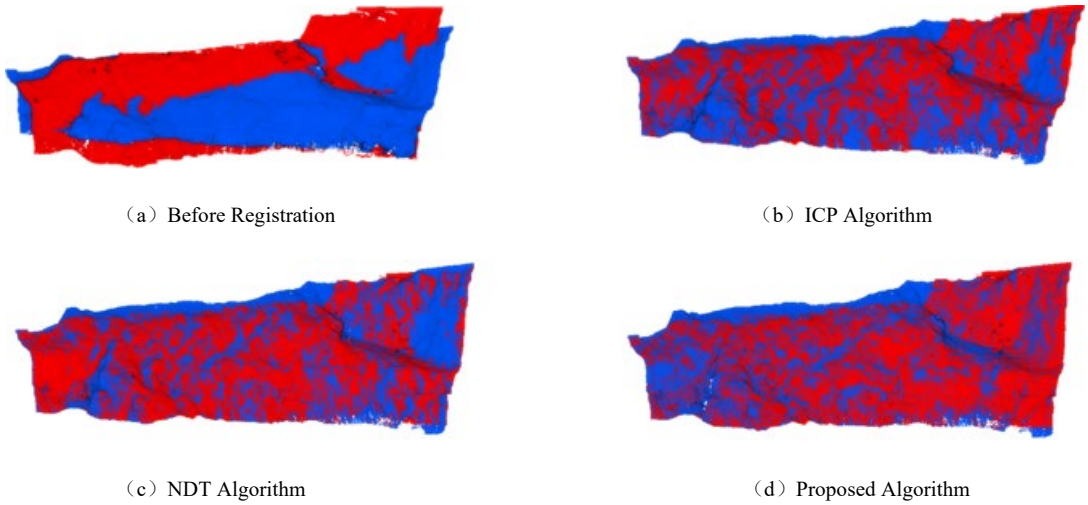
$$e_t = \frac{1}{M}\sum_{i=1}^{M} \left\| t_{m,i} - t_{g,i} \right\|_2 \quad (2)$$

where * and * denote the ground truth values of the rotation matrix R and translation vector t required for registration, respectively; * and * represent the estimated rotation matrix R and translation vector t corresponding to the *-th rigid transformation.

Table 1. Comparison Table

Registration Algorithm	Rotation Error(°)	Translation Error(m)	Registration Time（s）
ICP	0.0143	0.0529	23.89
NDT	0.0326	0.0271	26.52
Proposed Algorithm	0.0097	0.0159	39.97

As can be observed from the table above, the proposed algorithm achieves higher registration accuracy compared with the other methods. In particular, with respect to translation error, the proposed approach significantly outperforms the alternatives. In terms of rotation error, the performance of the proposed method is comparable to that of mainstream algorithms and is even slightly superior to the standard ICP algorithm. Regarding registration efficiency, the time consumed by the proposed algorithm is greater than that of the other methods, primarily because the extraction of stable rock features entails additional computational overhead. Over time, steep slopes undergo evident erosion-induced deformation, which introduces substantial registration errors in conventional ICP and NDT algorithms due to interference from deformed regions. By utilizing stable rock surfaces as the registration basis, the proposed method effectively mitigates such interference, thereby yielding optimal alignment results. A comparison of the real-world point cloud data before and after registration, as used in the experiment, is presented in Figure (1).



（a）Before Registration （b）ICP Algorithm

（c）NDT Algorithm （d）Proposed Algorithm

Figure 1. Comparison of Point Cloud Registration Algorithms

4. Summary

The control-free matching algorithm proposed in this paper aims to explore a registration methodology applicable to complex steep slopes that eliminates the need for manually deployed control points and effectively mitigates interference from unstable surface features. By minimizing systematic alignment errors across multi-temporal scans, this approach constitutes a critical component for the precise monitoring of areal deformable bodies.

References

[1] Rusinkiewicz S, Levoy M. Efficient variants of the ICP algorithm[C]Proceedings third international conference on 3-D digital imaging and modeling. IEEE,2001:145-152.

[2] Segal A, Haehnel D, Thrun S. Generalized-ICP[C]Robotics: science and systems.2009,2(4):435.

[3] Kenji K, Masashi Y, Shuji O, et al. Globally Consistent 3D LiDAR Mapping With GPU-Accelerated GICP Matching Cost Factors[J]. IEEE ROBOTICS AND AUTOMATION LETTERS,2021,6(4):8591-8598.

[4] Aiger D, Mitra N J, Cohen-Or D. 4-points congruent sets for robust pairwise surface registration[M]ACM SIGGRAPH 2008 papers.2008:1-10.

[5] Kang C, Geng C, Lin Z, et al. Point Cloud Registration Method Based on Geometric Constraint and Transformation Evaluation[J]. Sensors, 2024,24(6).

[6] Rusu R B, Blodow N, Beetz M. Fast point feature histograms (FPFH) for 3D registration[C] 2009 IEEE international conference on robotics and automation. IEEE,2009:3212-3217.

[7] Han T, Zhang R, Kan J, et al. A Point Cloud Registration Framework with Color Information Integration[J]. Remote Sensing,2024,16(5).

[8] Makovetskii A, Voronin S, Kober V, et al. Point cloud registration based on multiparameter functional[J]. Mathematics, 2021,9(20):2589.