High-Resolution UAV-Videogrammetry for Discontinuity Mapping in Steep Rock Slopes

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Abstract: Characterizing rock mass discontinuities in steep and complex terrain is a critical challenge in geotechnical engineering. Conventional field surveys are often unsafe and provide limited data, while standard UAV-based photogrammetry can be constrained by fixed flight plans and conclusions. This study presents a UAV-videogrammetry workflow for generating high-resolution, spatially accurate 3D models of rock slopes for detailed discontinuity analysis. By capturing continuous 4K video with a UAV in a dynamic, free-flight mode, we achieve dense surface coverage, even in geometrically complex areas like overhangs and recessed zones. A novel semi-georeferencing technique using coded targets enables precise model alignment in a local coordinate system without requiring GNSS, enhancing field applicability. Comparative analysis demonstrates that this approach yields a 20-fold increase in point cloud density and superior orientation accuracy (RMSE of 2° for dip, 7° for dip direction) compared to conventional methods. The resulting high-fidelity models allow for more complete joint set identification and a more comprehensive kinematic stability assessment, providing a safer, more efficient, and scalable solution for rock slope characterization.

Keywords: ***UAV-Videogrammetry, Rock mass discontinuities, 3D point cloud.***

Introduction

The stability of rock slopes is fundamentally governed by the geometry and orientation of discontinuities such as joints, fractures, and bedding planes. Accurate characterization of these features is essential for reliable engineering design and hazard assessment (Wang et al., 2020). However, traditional methods like manual scanline surveys are often limited in scope, pose safety risks on steep or unstable slopes, and may fail to capture the full complexity of the fracture network.

In recent years, Unmanned Aerial Vehicles (UAVs) have become a valuable tool for remote rock mass characterization (Riquelme et al., 2014). Standard UAV photogrammetry, however, typically relies on predefined flight paths and discrete image capture, which can lead to inconsistent resolution, data gaps in occluded areas (e.g., overhangs), and difficulty in adapting to complex geological structures in real-time (Elkhrachy, 2021).

To address these limitations, this study explores the application of UAV-videogrammetry, a technique based on capturing continuous high-resolution video. This approach allows for dynamic flight control, enabling the operator to adjust the UAV's trajectory and viewing angle to ensure comprehensive coverage of intricate rock face geometries. The resulting high density of overlapping frames facilitates the reconstruction of exceptionally detailed and accurate 3D models. The primary objective is to demonstrate how UAV-videogrammetry, combined with a practical non-GNSS referencing method, improves the detection, classification, and kinematic analysis of rock mass discontinuities compared to conventional UAV survey methods.

Methodology

The workflow integrates UAV-based video acquisition, a novel semi-georeferencing technique, 3D model reconstruction, and discontinuity analysis.

UAV-Videogrammetry Data Acquisition

A DJI Phantom 4 Pro V2.0 UAV was used to capture 4K video at 60 frames per second. Unlike traditional methods, a "free flight" mode was employed, allowing the UAV to be manually navigated in real-time to focus on complex geological formations. This dynamic approach ensures that overhangs, recessed features, and multi-oriented fracture sets are captured with optimal resolution and high frame overlap. The continuous video stream provides a dense set of potential images for 3D reconstruction, far exceeding that of typical photogrammetric surveys.

3D Reconstruction and Georeferencing

Video frames were extracted from the 4K footage in Agisoft Metashape with a 7% frame step, ensuring >90% overlap between consecutive images. A dense 3D point cloud was generated using Structure-from-Motion (SfM) and Multi-View Stereo (MVS) algorithms.

To ensure spatial accuracy without relying on GNSS, a semi-georeferencing tool was developed. This tool consists of a printed sheet with four coded targets at known relative positions. The sheet is placed on the rock face, and its orientation is measured with a geological compass. This allows the 3D model to be accurately scaled and oriented within a local coordinate system, providing reliable dip and dip direction measurements for structural analysis.

Discontinuity Analysis

Discontinuity information was extracted from the final 3D model using two complementary methods:

Semi-Automated Plane Detection: The qFacet Kd-Tree algorithm in CloudCompare was used to automatically identify and extract planar features from the dense point cloud.

Manual Trace Mapping: Discontinuity traces were manually digitized as 3D polylines on the textured mesh. The orientation of the corresponding joint planes was then estimated from the 3D geometry of these traces using Principal Component Analysis (PCA) for curved traces and coplanarity analysis for intersecting traces.

The extracted discontinuity orientations were clustered into joint sets and used for kinematic stability analysis (planar, wedge, and toppling failures) in Dips software.

Results and Discussion

The UAV-videogrammetry method was compared against a conventional oblique UAV photogrammetry survey of the same rock slope.

Data Quality and Accuracy

The UAV-videogrammetry model demonstrated vastly superior quality. The resulting point cloud was exceptionally dense, exceeding 45,000 points/m^2, an order of magnitude greater than that produced by the conventional survey. This high density yielded clearer surface textures and more sharply defined fracture traces, which are critical for accurate interpretation.

Validation against field measurements confirmed the model's high fidelity. Orientation errors were minimal, with a Root Mean Square Error (RMSE) remaining below 3° for dip angle and under 7° for dip direction. This level of accuracy confirms the reliability of the semi-georeferencing tool for precise structural analysis.

Discontinuity Detection and Kinematic Analysis

The high-resolution model enabled a significantly more complete inventory of structural features. Over 1,400 discontinuities were identified, representing an increase of more than 50% compared to the ~900 detected in the conventional photogrammetry dataset. This comprehensive dataset allowed for the classification of five distinct joint sets, whereas the conventional model only resolved three. The additional joint sets represent less prominent but potentially critical structural features that were otherwise missed.

This improved structural characterization translated into a more nuanced kinematic assessment. The UAV-videogrammetry data revealed a higher diversity of potential failure mechanisms, with stability risks distributed across multiple joint sets rather than being concentrated in just a few, as suggested by the conventional analysis. For instance, toppling risks were not confined to a single dominant set but were instead associated with several different discontinuity families. This highlights the proposed method's capacity to uncover complex structural controls on slope stability that might otherwise be overlooked.

Conclusion

This study confirms that UAV-videogrammetry is a significant advancement for characterizing rock mass discontinuities. By combining dynamic video capture with a practical, non-GNSS referencing tool, this method produces ultra-high-density 3D models that capture complex geological features with exceptional detail. The resulting high-fidelity data enables a more complete identification of discontinuity sets and a more reliable kinematic stability assessment than conventional methods. Overall, the proposed workflow offers a robust, safe, and scalable solution for improving geotechnical risk evaluation in challenging environments.

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