UAV-Based Discontinuity Analyses and Rock Fall Source Mapping in Alpine Terrain (Pletzachkogel/Tyrol/Austria)

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Abstract

Three major Holocene rock avalanches have sculpted the morphology of Mount Pletzachkogel (Tyrol, Austria), and rock fall processes continue to show recent activity. Coalescing sets of discontinuities and block moulds exposed in the steep and rugged limestone cliffs exemplify the broad spectrum of rotational and translational block failure modes to which the mountain is prone. As personnel safety concerns strongly limit the ability to access the 200 m high rock cliffs to make traditional structural field measurements, Unmanned Aerial Vehicle (UAV) photogrammetric surveys were performed with a compact portable multicopter. The UAV survey provided a georeferenced point cloud and Digital Terrain Model of sufficient resolution and accuracy to permit efficient extraction of structural geologic measurements by using different open source software packages. This research focuses on comparing discontinuity measurements extracted from the point cloud using manual, semi-automated, and automated techniques, to field measurements made with a geologic compass. The overall workflow of digital image processing and related structural measurement extraction is described, together with data validation procedures. The workflow described herein provides an efficient means for obtaining comprehensive and accurate data sets that mitigate personnel access constraints, are fully auditable and archivable. With increased applications of UAVs for geologic mapping and documentation, such procedures are sure to see rapidly increasing deployment, particularly in alpine terrain.

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UAV photogrammetry • Discontinuities
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1 Introduction

Assessment of rock fall hazards in steep mountainous terrain having high relief is often encumbered by personnel access constraints and safety concerns. Photogrammetry based on Unmanned Aerial Vehicle (UAV) data collection platforms greatly enhance observational access to restricted terrain, while also providing 3D georeferenced point clouds of sufficient resolution and accuracy to permit reliable digital structural geologic measurements. The primary aim of this study is to evaluate the efficacy of deploying small, portable UAVs in the context of rock fall source area analyses. This evaluation is based on comparing point cloud derived digital discontinuity orientation measurements to structural measurements made in the field with a geologic compass. Methods for extracting the structural measurements from the point cloud included manual/interactive techniques as well as semi-automated and automated discontinuity detection algorithms.

2 Site Conditions

Pletzachkogel is located in Tyrol, Austria and has a peak elevation of 1549 m a.s.l. (Fig. 1). The mountain is located at the southern margin of the Northern Calcareous Alps, which consist primarily of Mesozoic sedimentary rocks, featuring polyphase and heteroaxial folding and faulting (Ampferer 1908; Schmid et al. 2004). As depicted in Fig. 1, three major Holocene landslides have sculpted the morphology of Pletzachkogel (Patzelt 2012). The investigated rock fall source area is composed of reddish-grey massive to obscurely bedded, rigid breccia (lower Jurassic).

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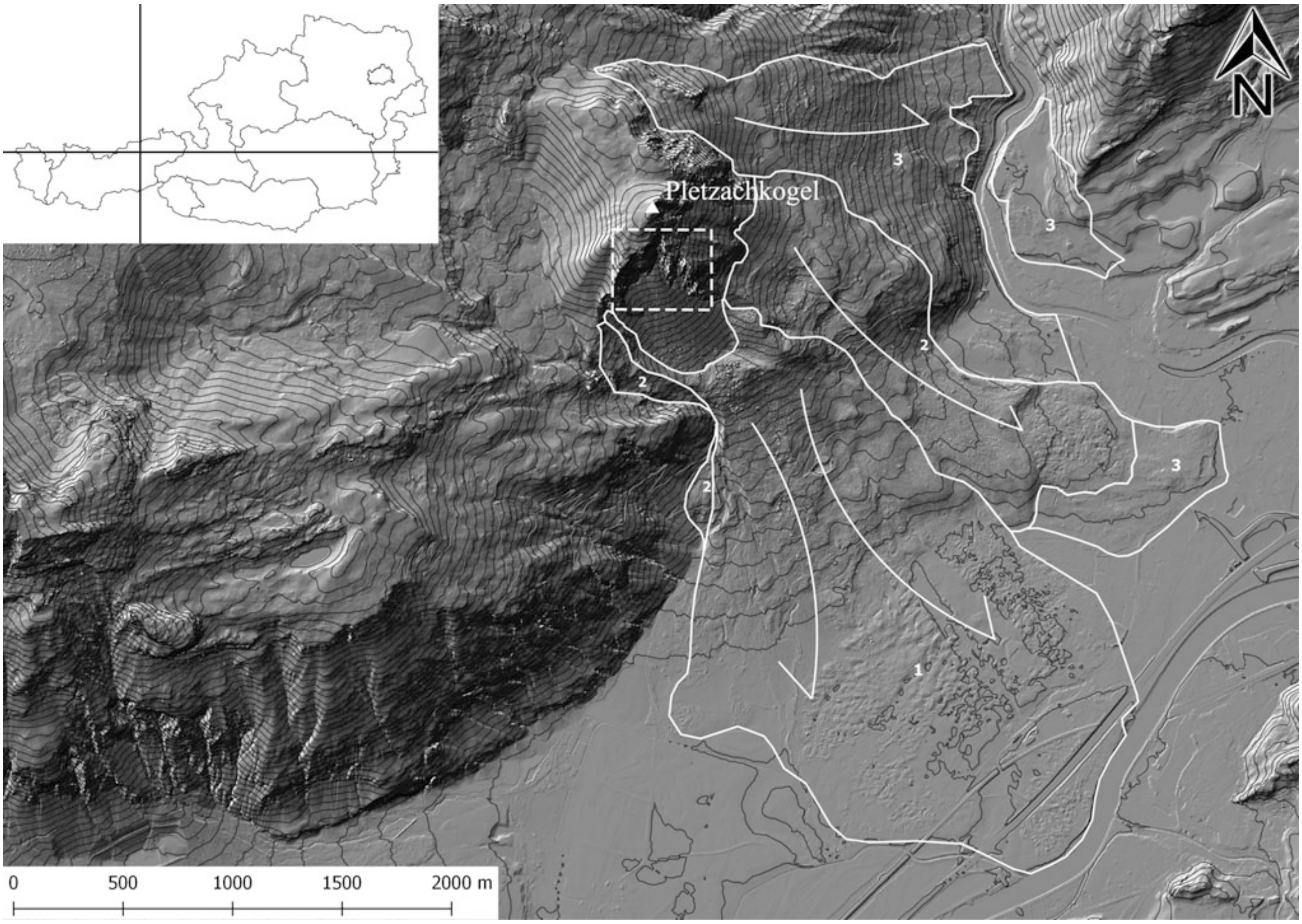

Fig. 1 Hillshade DEM from 1 m Airborne laser scan (contour interval 20 m) showing the topography of Pletzachkogel and landslide deposits detached thereof (marked with white lines, 1—last-(120–240 AD), 2—middle Holocene and 3—late Pleistocene—landslide (Patzelt 2012). Dashed rectangle at Pletzachkogel SE-face indicates UAV-surveyed scarp area

The fractured rock mass is characterised by different sets of discontinuities (brittle joints, some folded bedding planes) with rough, stepped and wavy surfaces on mm-, cm- and m-scales, respectively.

Topographically, Pletzachkogel is dominated by a near vertical and southeast facing cliff having a maximum relief of >200 m. On its southeast side Pletzachkogel is bordered by a series of prominent vertical rock towers that are up to 200 m high and are referred to as the “rock buttress” (Fig. 2). The cliff and rock buttress represent the head scarps of major landslides that occurred at around 120–240 AD (Patzelt 2012). Subsequent to these landscaping events, rock falls have represented an ongoing geologic process. The most recent significant rock falls occurred in 2011 and 2015, with debris volumes exceeding 1000 m^3 (Fig. 2). The rock fall source areas are located above a 300 m high talus fan, featuring dangerous site access exposed to potential rock fall hazards.

3 Methodology

3.1 UAV Photogrammetric Survey and Image Processing

Aerial photographs were acquired with the DJI Mavic Pro (“Mavic”) quadrocopter. The Mavic is well suited to alpine environments by virtue of its compactness, flight duration and photographic capabilities. Technical specifications of the Mavic are summarized in Table 1. With a standard GPS accuracy of >5 m, the Mavic’s on-board GPS system is not sufficiently accurate for direct georeferencing of the photogrammetric point cloud, requiring indirect georeferencing with precisely surveyed ground control points (GCPs). The used GCPs are specially fabricated optical targets, whose center coordinate can be identified and precisely selected directly on overlapping aerial photographs.

Fig. 2 The southeastern cliff face of the Pletzachkogel (left) and the rock buttress (right). The source areas and deposits of the 2011 and 2015 rock falls are indicated by freshly exposed rocks in the buttress area. Note major joints shaping the rock mass

Table 1 DJI Mavic Pro key technical specifications (DJI 2017)

UAV	Weight [g]	734
	Size (folded) [mm]	83 × 83 × 198
	Max. flight time [min]	27
Camera	Sensor type	CMOS
	Sensor format	1/2.3
	Sensor dimensions [pixels]	4000 × 3000
	Sensor dimensions [mm]	6.2 × 4.6
	Image resolution [Mpixels]	12.35
	Focal length [mm]	28
	ISO	100–1600

In consideration of model size and computational effort, the UAV survey area was spatially divided into three “chunks”. Chunk 1 and 2 include the buttress towers, and Chunk 3 comprises the SE-facing main cliff (see Fig. 2). Six GCPs were established for each chunk. Due to a multitude of topographic obstructions and flight hazards, UAV photograph acquisition was performed in a manual flight mode rather than autonomously (pre-programmed flight plan). In total, 853, 779, and 1931 overlapping photographs were acquired for Chunks 1, 2, and 3, respectively.

The raw photographs were manually sorted (e.g. blurry, heavily over- or underexposed, or redundant images were removed from the data set) and georeferenced point clouds were then generated applying the software *Agisoft PhotoScan Professional* (Agisoft 2017).

3.2 Digital Mapping and Kinematic Analysis

Two plugins for the open source 3D point cloud processing software *CloudCompare* (CC) (version 2.9. beta) were used to extract plane orientations (CloudCompare 2017): *Facets* and *Compass*.

Facets is a CC plugin for fully automatic structural data extraction (Dewez et al. 2016), which divides the point cloud into clusters of adjacent points and employs a least square plane fitting algorithm. Following user defined criteria of co-planarity, the clusters are reassembled in a three-step process: (1) elementary facets corresponding to small fragments of planes are computed; (2) elementary planes are then re-clustered into encompassing planes; and (3) parallel planes are merged into plane families. The end result is a number of polygons that are color coded according to their spatial orientation (azimuth/dip). The data can be exported as.csv or.shp files, or analyzed directly in CC (Dewez et al. 2016). The user defined input parameters selected for the *Facets* analysis are summarized in Table 2.

Compass is an additional CC plugin for extracting and exporting manual or semi-automated structural measurements from point clouds using a plane-, trace- and lineation-measurement tool (Thiele et al. 2017). Using a least square algorithm, *Compass* fits a plane to a group of sampled points. Selection of points is facilitated by an adjustable sampling-circle around the cursor. The *plane-tool* is applicable to exposed surfaces, while the *trace-tool* can extract orientation based on the geometry of a discontinuity edge intersecting an irregular outcrop surface. The start and end points of a discontinuity trace are specified, and the tool finds the linking “structural trace” using a “least cost path” algorithm. A planar surface is then fitted to each trace with a least square algorithm to obtain an “estimate of the structure orientation”. The *lineation-tool* simply measures the trend and plunge of a straight line between two points.

On the basis of UAV derived structural measurements (orientations of discontinuities), simple kinematic analyses were performed to obtain an initial estimate of block failure mode tendencies. The main focus of the kinematic analyses included the Pletzachkogel southeastern cliff face and neighboring rock buttress area. The kinematic conditions for planar sliding, wedge sliding and toppling were manually evaluated (e.g. Wyllie et al. 2004) and the stereonets generated with the programs *Dips* (Rocscience Inc. 2018) and *Stereonet* (Allmendinger et al. 2012; Cardozo and Allmendinger 2013).

Table 2 Input parameters for the facets “fast marching approach.”

Octree level	10
Use retro projection error for propagation	Yes
Max distance @99%	0.213
Min points per facet	3500
Max edge length	0.7

4 Results

For Chunk 1 a dense point cloud (DPC) consisting of 41,805,462 points was generated with a ground resolution of 3.04 cm/pix and a reprojection error of 1.11 pix. The DPC for Chunk 2 consists of 49,762,919 points with a ground resolution of 2.3 cm/pix and a reprojection error of 1.23 pix. For Chunk 3, the DPC consists of 42,481,210 points with a ground resolution of 3.42 cm/pix and a reprojection error of 1.68 pix. In the areas of primary interest (i.e. bedrock outcrops), the image overlap is greater than nine. A portion of the DPC covering the southeastern cliff face is shown in Fig. 3a.

With the CC plugin *Compass*, 1394 structural measurements were extracted, and with the plugin *Facets*, 5238 planes were extracted. As shown in Fig. 3, there are two main orientation clusters. For the *Compass* measurements, the cluster centers have a dip direction/dip of 127/68(JS1) and 183/88(JS2), and for the *Facets* measurements, the corresponding center orientations are nearly identical at 124/69(JS1) and 180/86(JS2). The joint set orientations determined on the basis of point cloud- and manual field measurements are summarized in Table 3.

As indicated therein, the point cloud derived measurements underrepresent a third discontinuity set having an orientation of approximately 280/60(JS3). The underrepresentation of this joint set is related to the characteristically small surface areas of joint faces exposed in the outcrops.

Discontinuity set orientations measured for the rock buttress are similar, but scattering of the results is more significant than for the southeastern cliff face. The underrepresented third joint set, having an orientation of 270/70, was also detected in the point cloud for the rock buttress.

5 Interpretation

In the simple kinematic analyses, the entire populations of structural measurements derived from the DPCs were utilized as input and separated into the measurements from the southeastern cliff face and from the rock buttress

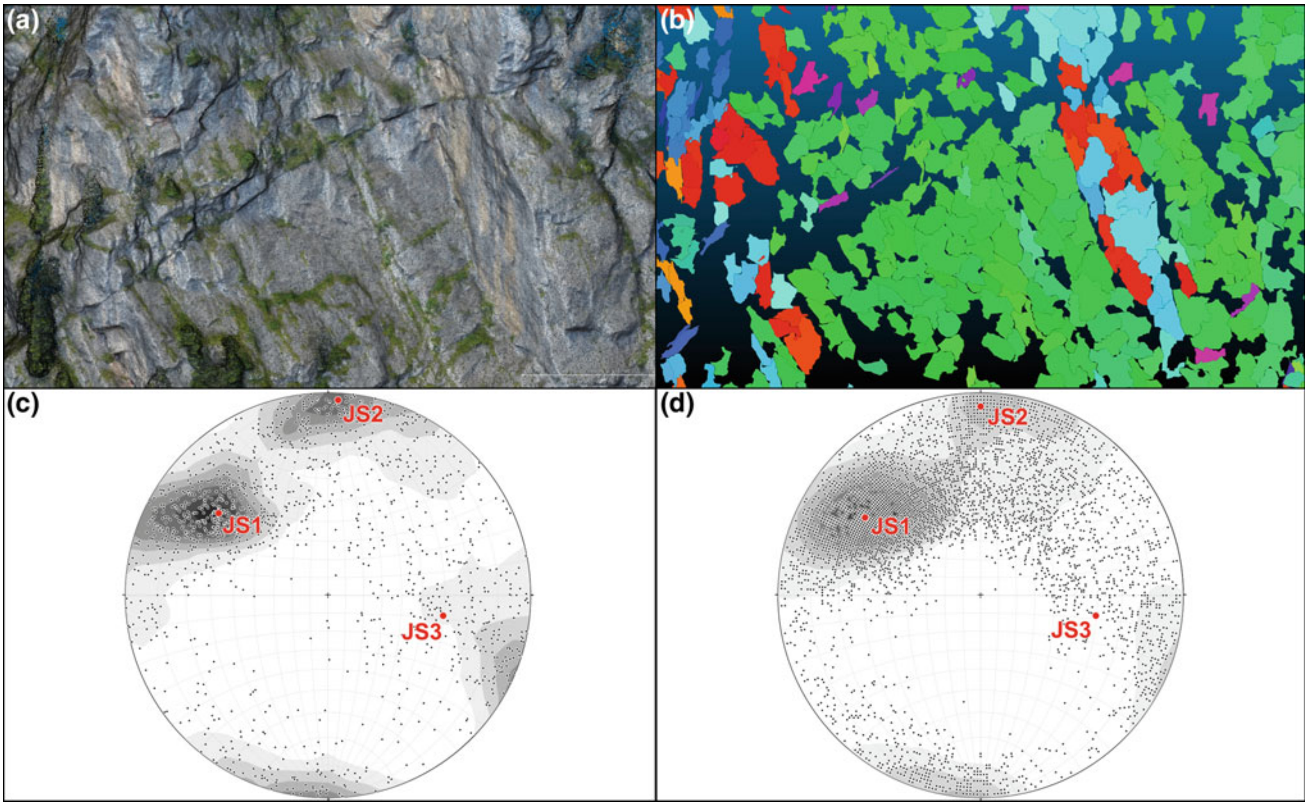

Fig. 3 **a** Portion of dense point cloud covering the southeastern cliff face; **b** automatically extracted planes with *Facets*; **c** equal angle, lower hemisphere, stereographic projection of the 1394 poles from *Compass*; and **d** stereographic projection of the 5238 poles from *Facets*

Table 3 Average joint set orientations (dip direction/dip) obtained from photogrammetric point clouds (SE-facing main cliff and rock buttress), and from manual field measurements in the investigated area

	Southeastern cliff face	Rock buttress	Field measurements
Joint set 1	129/64	116/75	103/65
Joint set 2	181/88	202/87	190/80
Joint set 3	280/60	270/70	270/35

(see Sect. 3). The southeastern cliff face orientation was taken at 140/70, and kinematic analyses for the rock buttress area explicitly considered the near-vertical columnar geometry of the rock towers by introducing a composite convex free-space formed by the intersection of slope orientations: 110/75, 200/75, and 290/75. The analysis results for the southeastern cliff are shown in Fig. 4. A mean joint friction angle of 35° was estimated, in view of discontinuity properties observed in the field and literature data (e.g. Barton 1976). The analyses indicate that planar sliding is kinematically permissible along Joint Set 1, as is wedge sliding along the intersection lines Joint Sets 1 and 2. Concerning the representative mean slope orientation (SE-facing), there are comparatively few structural elements that are susceptible to toppling failure. However, in a more detailed view also some other oriented slope faces, may be prone to planar and/or toppling failure modes (e.g. S- to SSW-facing areas, see Fig. 4a).

Analysis results for the rock buttress area are summarized in Fig. 5. As shown, planar and toppling failure are kinematically permissible along every side of the rock towers, excluding the not free northern side. Due to the increased scattering of joint orientations at the rock buttress, the analyzed joint intersections produce a wide range of intersection lines meeting the kinematic requirements for wedge failure, notably along intersection lines plunging toward the south. The increased data scattering is possibly related to the near-vertical columnar structure of the rock towers, providing an opportune geometry for long-term relaxation of the rock mass in the absence of lateral stresses.

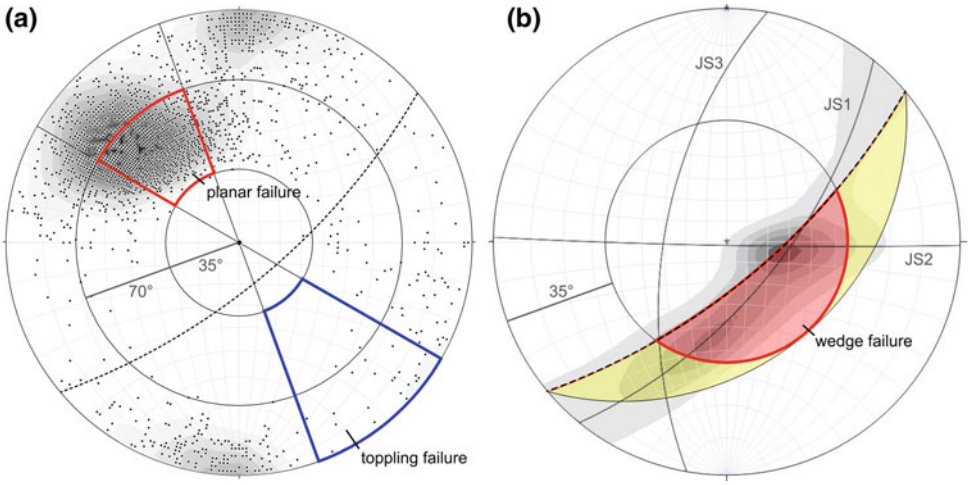

Fig. 4 Kinematic analysis of southeastern cliff (equal angle, lower hemisphere stereographic projection of discontinuity poles): **a** structural elements susceptible to planar and toppling failure (inner circle: friction angle = 35°; intermediate circle: slope angle = 70°); and **b** density contour plot of 2,413,850 joint intersection lines, with red shaded domain indicating structural elements susceptible to wedge failure (inner circle: friction angle = 35°). Free slope surface is indicated as dashed great circle and mean joint orientations as grey great circles (JS1-3)

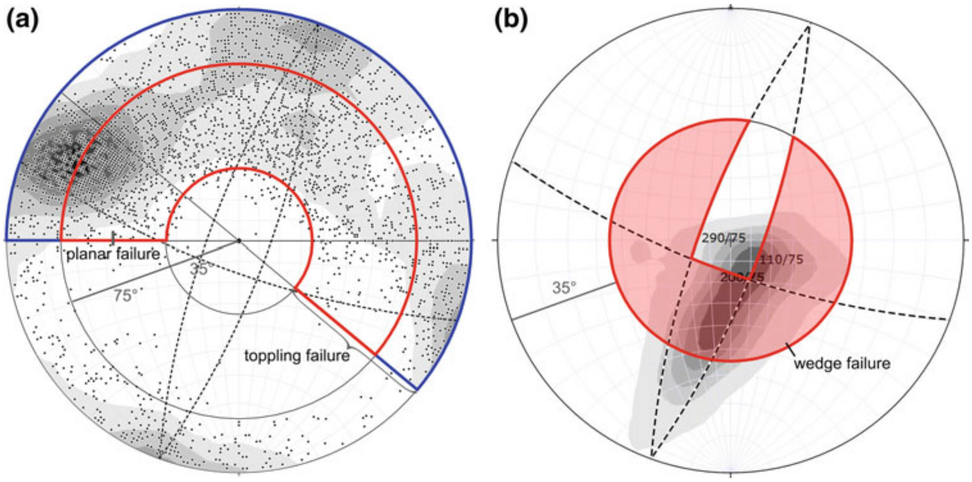

Fig. 5 Kinematic analysis of rock buttress area (equal angle, lower hemisphere stereographic projection of discontinuity poles): **a** structural elements susceptible to planar and toppling failure (inner circle: friction angle = 35°; intermediate circle: slope angle = 75°); and **b** density contour plot of 4,618,676 joint intersection lines, with red shaded domain indicating structural elements susceptible to wedge failure (inner circle: friction angle = 35°). Free slope surfaces are indicated as dashed great circles

6 Conclusions

Compact portable drone platforms for UAV photogrammetry provide an unprecedented ability to capture high resolution 3D georeferenced structural geologic data. Considering the great efficiency with which data can be acquired, UAV–based survey methods are sure to see rapidly increasing deployment, particularly in alpine terrain where site access limitations and personnel safety concerns are significant.

The UAV workflow presented herein has been applied for rock fall source area analysis, and greatly facilitates identification of rock blocks that meet kinematic requirements for a variety of block detachment modes. A key step in the workflow involves extraction of discontinuity orientations from the 3D point cloud. For developing large data sets, efficiency becomes increasingly important, and automated or semi-automated point cloud orientation extraction tools are necessary. The plugins *Facets* and *Compass* developed for the open source software CloudCompare permit automated and semi-automated measurements, respectively, and coincide well with data obtained from manual field measurements. As a result, three different oriented main joint sets were identified, and analyzed concerning potential block failure modes. The data sets obtained are sufficient for performing accurate structural geological analyses of inaccessible areas, and thus can substantially support ground-based geologic field surveys.

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