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Sequential digital elevation models of active lava flows from ground-based stereo time-lapse imagery

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ABSTRACT

We describe a framework for deriving sequences of digital elevation models (DEMs) for the analysis of active lava flows using oblique stereo-pair time-lapse imagery. A photo-based technique was favoured over laser-based alternatives due to low equipment cost, high portability and capability for network expansion, with images of advancing flows captured by digital SLR cameras over durations of up to several hours. However, under typical field scale scenarios, relative camera orientations cannot be rigidly maintained (e.g. through the use of a stereo bar), preventing the use of standard stereo time-lapse processing software. Thus, we trial semi-automated DEM-sequence workflows capable of handling the small camera motions, variable image quality and restricted photogrammetric control that result from the practicalities of data collection at remote and hazardous sites. The image processing workflows implemented either link separate close-range photogrammetry and traditional stereo-matching software, or are integrated in a single software package based on structure-from-motion (SfM). We apply these techniques in contrasting case studies from Kilauea volcano, Hawaii and Mount Etna, Sicily, which differ in scale, duration and image texture. On Kilauea, the advance direction of thin fluid lava lobes was difficult to forecast, preventing good distribution of control. Consequently, volume changes calculated through the different workflows differed by ~10% for DEMs (over ~30 m^2) that were captured once a minute for 37 min. On Mt. Etna, more predictable advance (~3 m h^{-1} for ~3 h) of a thicker, more viscous lava allowed robust control to be deployed and volumetric change results were generally within 5% (over ~500 m^2). Overall, the integrated SfM software was more straightforward to use and, under favourable conditions, produced results comparable to those from the close-range photogrammetry pipeline. However, under conditions with limited options for photogrammetric control, error in SfM-based surfaces may be difficult to detect.

1. Introduction

Despite recent advances in our capability for modelling lava flows (e.g. Crisci et al., 2004; Favalli et al., 2005; Harris and Rowland, 2001; Hidaka et al., 2005) significant challenges remain. One area of uncertainty is in the parameters that describe the lava rheology; however, in most cases, such parameters are not possible to measure directly in the field due to hazards (rockfall and others), and the apparent viscosities (e.g. 10^2–10^5 Pa s) and temperatures (usually >1100 °C at the vent) involved. Nevertheless, bulk rheological properties can be estimated from measurements of the slope, and flow velocity and dimensions (Jeffreys, 1925). At flow fronts, appropriate measurements can be made from sequential digital elevation models (DEMs) acquired as a flow advances over new ground.

DEM sequences can be obtained by repeated laser scanner surveys, and both terrestrial and airborne instruments have been previously used to investigate active flows (Favalli et al., 2010; James et al., 2009). Nevertheless, terrestrial instruments are expensive (e.g. >£30 k) and can be difficult to transport into remote and hazardous areas, and airborne surveys are not generally repeated on the minute-to-hourly timescales required to capture flow dynamics. Here, we explore the potential of using camera-based methods with stereo, ground-based time-lapse image sequences to provide the temporal and spatial data required. The approach can be fully implemented for <£2 k and can be easily extended by adding

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further cameras to the system to enhance accuracy or expand spatial coverage.

Photogrammetry has long history of use in environmental and natural hazard research, using both aerial- and satellite-imagery (Baldi et al., 2000; Diefenbach et al., 2012; Kaab, 2002; Schilling et al., 2008), and also ground-based imaging (Brecher and Thompson, 1993; Chandler et al., 2002; Rieke-Zapp and Nearing, 2005). In volcanological applications, aerial techniques have been recently joined by 3D reconstructions of terrain and slow moving lava flows using ground-based and single camera multi-view techniques (Cecchi et al., 2003; James et al., 2007; Ryan et al., 2010), and computer-vision based structure-from-motion and multi-view stereo (SfM–MVS) software is now also being employed (James et al., 2012; James and Varley, 2012; Tuffen et al., 2013). However, single camera methods are not practical for rheological studies of more rapidly moving lavas, where rates of change necessitate simultaneous image acquisition and a multi-camera time-lapse approach. Time-lapse imagery is collected at many volcanoes (e.g. Herd et al., 2005; Major et al., 2009; Yamashina et al., 1999), but is usually acquired from semi-permanent installations for relatively general monitoring purposes, and quantitative analyses have been restricted to tracking individual points. For studying mobile active lava flows, a relatively close range system (e.g. operating over a few 10's–100's m) is required, that can be set up rapidly to capture synchronised image pairs (or more) from which near instantaneous DEM-snapshots of rapidly evolving terrain can be derived.

Working in remote, uncontrolled and dynamic environments provides challenges in the practical application of photogrammetric techniques. For example, the location of the lava flows may initially not be precisely known and can unexpectedly change over time. Thus, control and camera positions cannot be pre-planned and have to be determined on site, whilst forecasting the future path of the flow. Image capture can be hindered by inclement weather (e.g. rain, wind) and variable illumination conditions, and parts of the scene can often be intermittently obscured by steam and volcanic gases. Weather and unstable ground mean that in most cases, camera orientations cannot be guaranteed to remain constant. Consequently, data processing techniques need to be able to tolerate changing and variable quality photogrammetric network geometries and, in order that the large data volumes of multiple camera sequences can be handled efficiently, the processing pipeline must be able to cope with the image variability that such practical and environmental difficulties produce.

Traditional software packages derived for use with aerial imagery can be capable of producing DEMs from oblique imagery (Chandler, 1999), but they lack any straightforward automation for generating multiple DEMs from temporal sequences. Many commercial close range photogrammetry packages offer sequence analysis, but assume fixed down-sequence imaging geometry, which is unsuitable for our mobile field deployments. Consequently, we constructed a semi-automated pipeline by linking a close range photogrammetry software package that is capable of continuous down-sequence determination of imaging geometry, with a dense image matching algorithm (an outline of this workflow was given in Robson and James (2007)). In addition, we explore the use of an integrated SfM-based software package where, for the purposes of this paper, we distinguish SfM-based software from 'traditional' photogrammetry by its capability to derive object space information (i.e. 3D surface coordinates and camera positions) without a priori information such as control points or camera positions. The automation and robust nature of SfM-based approaches (e.g. Brown and Lowe, 2005) is making them of increasing interest to a wide range of geoscientists. However, they are designed for use with relatively large numbers of images, overall accuracies are generally poorer than those of rigorous photogrammetry (James and Robson, 2012) and their performance with stereo pairs is unexplored for environmental applications.

We use two contrasting case studies driven by natural hazards research (Fig. 1). Firstly, the advance of a pahoehoe lava flow lobe, with a decimetre- to metre-scale thickness, on Kilauea, Hawaii, was recorded over a period of 37 min (Hamilton et al., 2013). Pahoehoe lava has a relatively smooth surface, and advances by sequentially extruding new lobes whilst the body of the flow behind steadily inflates (Fig. 1a). In comparison, the second case study involves a ~3 h sequence of a rubble-covered 'a'ā lava flow, several metres thick, on Mount Etna, Sicily (Fig. 1b). The 'a'ā flow advance rate was less than that of the pahoehoe flow, so the studies cover scenarios which differ in scale, surface texture and velocity. Between them, the case studies also illustrate many of the practical difficulties involved with such work, for example, intermittent occlusions (Fig. 1c), camera motions (from wind and manual adjustments), periods of poor visibility (Fig. 1d), and relatively weak photogrammetric control. Consequently, the goals of this paper are to

1. describe the technical approach and practical implementation of mobile stereo time-lapse data collection from digital SLR cameras in challenging field environments,
2. detail the data processing automation required for efficient DEM extraction from such oblique, ground-based stereo sequences (in particular, explore different approaches for deriving camera orientations), and
3. assess the quality of the resulting DEM sequences.

Although dense stereo matching forms an integral component of the DEM generation process, due to the large number of possible matchers that could be used, we leave matcher comparisons to further work, focusing more on the continuous determination of imaging geometry through the sequences.

2. Methods

Our framework for DEM-sequence reconstruction comprises four stages; (1) deployment and measurement of control targets and collection of images in the field, (2) processing an initial convergent image network to refine camera models and control target positions, (3) using the results to constrain the stereo sequence processing and hence derive a geo-referenced 3D point cloud for each epoch of the sequence and, (4) deriving DEMs from these point clouds.

For a rigorous photogrammetric approach to the processing, we used the Vision Measurement System (VMS, www.geomsoft.com, Robson and Shortis) close range photogrammetry software, which provides control target detection, automated target tracking and photogrammetric processing (including camera calibration) for both static network- and automated sequence-style projects. To generate high measurement densities for DEM generation, VMS has been previously linked to the dense image matcher Gotcha (Day and Muller, 1989). Here, we retain this link because of the demonstrated quality of Gotcha results for active lava surfaces (James et al., 2012), but other dense matchers could have been used.

For image sequence processing in a single software package, we used PhotoScan Pro (v.0.9.1). Like VMS, PhotoScan offers a dedicated workflow style for sequence processing; however, in PhotoScan this is constrained to scenarios in which relative camera orientations are fixed throughout the sequence. With the practicalities of the field-based measurements preventing this constraint from being satisfied, epochs had to be processed effectively