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Optimising UAV topographic surveys processed with structure-from-motion: Ground control quality, quantity and bundle adjustment

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ABSTRACT

Structure-from-motion (SfM) algorithms greatly facilitate the production of detailed topographic models from photographs collected using unmanned aerial vehicles (UAVs). However, the survey quality achieved in published geomorphological studies is highly variable, and sufficient processing details are never provided to understand fully the causes of variability. To address this, we show how survey quality and consistency can be improved through a deeper consideration of the underlying photogrammetric methods. We demonstrate the sensitivity of digital elevation models (DEMs) to processing settings that have not been discussed in the geomorphological literature, yet are a critical part of survey georeferencing, and are responsible for balancing the contributions of tie and control points. We provide a Monte Carlo approach to enable geomorphologists to (1) carefully consider sources of survey error and hence increase the accuracy of SfM-based DEMs and (2) minimise the associated field effort by robust determination of suitable lower-density deployments of ground control. By identifying appropriate processing settings and highlighting photogrammetric issues such as over-parameterisation during camera self-calibration, processing artefacts are reduced and the spatial variability of error minimised.

We demonstrate such DEM improvements with a commonly-used SfM-based software (PhotoScan), which we augment with semi-automated and automated identification of ground control points (GCPs) in images, and apply to two contrasting case studies — an erosion gully survey (Taroudant, Morocco) and an active landslide survey (Super-Sauze, France). In the gully survey, refined processing settings eliminated step-like artefacts of up to ~50 mm in amplitude, and overall DEM variability with GCP selection improved from 37 to 16 mm. In the much more challenging landslide case study, our processing halved planimetric error to ~0.1 m, effectively doubling the frequency at which changes in landslide velocity could be detected. In both case studies, the Monte Carlo approach provided a robust demonstration that field effort could by substantially reduced by only deploying approximately half the number of GCPs, with minimal effect on the survey quality. To reduce processing artefacts and promote confidence in SfM-based geomorphological surveys, published results should include processing details which include the image residuals for both tie points and GCPs, and ensure that these are considered appropriately within the workflow.

1. Introduction

Unmanned aerial vehicle (UAV) surveys are being increasingly used to collect high resolution airborne imagery in a wide variety of environmental and geomorphological environments, including agricultural (Marzolff and Poesen, 2009; Marzolff et al., 2011; d'Oleire-Oltmanns et al., 2012; Eltner et al., 2015), landslide (Niethammer et al., 2012; Lucieer et al., 2014; Turner et al., 2015), coastal (Delacourt et al., 2009; Harwin and Lucieer, 2012; Goncalves and Henriques, 2015), fluvial (Lejot et al., 2007; Hervoue et al., 2011; Flener et al., 2013; Fonstad et al., 2013; Tamminga et al., 2015; Woodget et al., 2015) and glacial (Whitehead et al., 2013; Immerzeel et al., 2014) studies. Typical requirements are to derive surface change from image orthomosaics and detailed digital elevation models (DEMs) which are produced from photogrammetric processing of images.

Such processing is usually carried out with 3-D reconstruction software based on structure-from-motion (SfM) and multi-view stereo (MVS) algorithms. However, a recent review of published geomorphological studies (covering both aerial and ground-based work)

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demonstrated order of magnitude variations in relative survey measurement quality (Smith and Vericat, 2015). Although some of this variability is likely to result from differences in how error is assessed (Smith and Vericat, 2015), it strongly suggests that substantial improvements in survey design or processing (or both) should be possible in many cases. Furthermore, early ground-based SfM-MVS analysis of spatio-temporal erosion rates suggested that measurement precisions of ~1/1000 of the viewing distance could be achieved (James and Robson, 2012), but the ratios of root mean square error (*RMSE*) to viewing distances for >40 published surveys have a median value of ~1/640 (Smith and Vericat, 2015). Unfortunately, the use of user-friendly SfM-MVS software does not promote consideration of the processing parameters involved, and the lack of details means that it is not possible to understand fully the underlying sources of error in geomorphological studies. Here, we show that considering some of the photogrammetric principles involved will enable geomorphologists to truly unlock the potential of SfM-based surveys and better exploit the millimetre-to-centimetre resolution of UAV imagery. Through illustrating the sensitivity of DEMs to the values used for processing settings, we highlight the additional information that should be provided with surveys in order to increase confidence in the results.

Georeferencing forms a fundamental part of topographic surveys and, for SfM-MVS work, dense deployments of carefully-measured ground control points (GCPs) are generally used, which can represent a substantial proportion of the overall survey effort. However, it is critical that control data are incorporated suitably within the image processing in order to avoid adversely affecting DEM accuracy, and this includes weighting their contribution appropriately within the processing, and ensuring that any outliers in either survey or image measurement data are identified and eliminated. SfM-MVS software does not generally provide the detailed quality assessment diagnostics necessary for rigorous photogrammetric analysis. Thus, a comprehensive understanding of DEM accuracy and the contribution of control measurements can be difficult to achieve, hindering generic improvements in GCP deployment and processing. One solution is to use SfM to initialise processing with conventional aerial (Rosnell and Honkavaara, 2012) or oblique photogrammetric (James and Robson, 2012) software, from which detailed analyses can be obtained, or to use software that combines aspects of both SfM and photogrammetry (e.g. MicMac, Pierrot-Deseilligny and Clery, 2011). However, the use of such integrated approaches presents an additional (steep) learning curve that will deter many SfM-MVS users.

Thus, here, we develop a Monte Carlo approach in order to (1) improve DEM accuracy and reproducibility, and (2) enable reduced field survey effort through a better understanding of GCP contributions with any of the above methods, but particularly when using SfM-MVS image processing alone. Underpinning our work is the appropriate handling of measurement error within SfM-MVS workflows; this is often poorly understood by users and somewhat hidden within ‘black box’ software. For example, to the authors' knowledge, the values of settings used to describe the precision of image measurements have never been reported in SfM-geoscience literature, although these are critical to obtaining accurate and repeatable results. To illustrate the importance of such settings, SfM-MVS software (PhotoScan, v.1.1.6) was used with manufacturer-recommended default values (see Section 3.1) to process a case study in this work, representing a reasonably typical UAV survey. Two DEMs were produced, one processed with and one processed without independently measured check points. Within the region covered by GCPs, the DEMs showed systematic step-like differences with amplitudes of up to ~50 mm, which corresponded with changes in image overlaps (Fig. 1a, b). Similar variations were augmented by broader differences between DEMs generated with different selections of equally well-distributed GCPs as control points (Fig. 1c; with RMS difference between the GCP-covered regions of the DEMs being 39 mm). In this case, the strong systematics resulted in volume differences in the western side of the survey of 173 m^3 (112 $\text{m}^3\ \text{ha}^{-1}$), with oppositely signed volume change on the east side of 676 m^3 (360 $\text{m}^3\ \text{ha}^{-1}$). These processing artefacts would represent important bias when comparing repeat surveys for understanding processes such as soil erosion. Such problems result from excessive influence of the relatively few ‘marker’ points used to identify GCP positions in the images, due to the default processing settings heavily over-weighting GCP observations within the processing. Consequently, without full reporting of all processing settings values used for surveys, the likelihood of DEM shapes being been substantially adversely affected by inappropriate settings cannot be discounted.

DEM accuracy assessments are often presented through calculating *RMSE* on check points, but the use of such statistics alone does not expose the presence of spatially systematic (i.e. non-random) error (Kyriakidis et al., 1999). The critical importance of spatially correlated

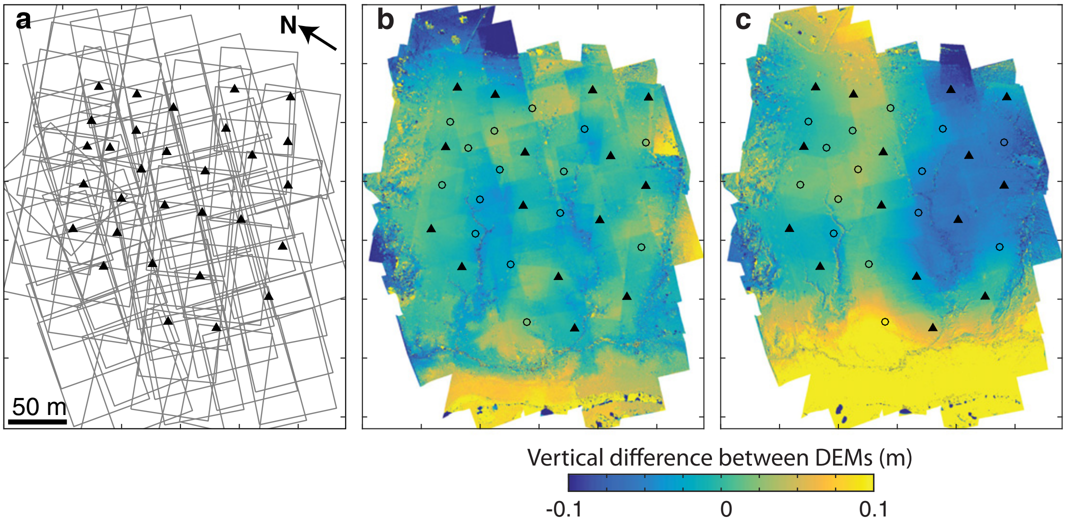

Fig. 1. DEM variations resulting from using PhotoScan (v.1.1.6) default or recommended processing settings in a self-calibrating bundle adjustment (‘marker accuracy’ = 5.0 mm, ‘projection accuracy’ = 0.1 pixels and ‘tie point accuracy = 4.0 pixels; see Section 3.1 for explanation of terms and Section 4 for details of the UAV survey and image set used). Unless otherwise specified, the GCP symbology used here applies throughout the figures. (a) Planimetric distribution of image outlines and GCP locations in the survey. (b) Vertical differences between two DEMs generated by processing the image set whilst using 15 GCPs as control points, but either with or without the check points present during processing. (c) DEM differences when different GCPs are used as control points — one DEM was generated using the GCPs identified by triangles as control points and the circles as check points, the other visa-versa.