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Reconstruction of extreme topography from UAV structure from motion photogrammetry

Francisco Agüera-Vega[a,*], Fernando Carvajal-Ramírez[a], Patricio Martínez-Carricondo[a], Julián Sánchez-Hermosilla López[a], Francisco Javier Mesas-Carrascosa[b], Alfonso García-Ferrer[b], Fernando Juan Pérez-Porras[b]

[a] Dept. of Engineering, Univ. of Almeria, Campus de Excelencia Internacional Agroalimentario, ceiA3, Spain
[b] Dept. of Graphic Engineering and Geomatics, Campus de Rabanales, University of Cordoba, Córdoba 14071, Spain

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ABSTRACT

The development of unmanned aerial vehicle photogrammetry over the last decade has allowed terrain that is very difficult for humans to access to be captured at very high spatial and temporal resolutions. This paper deals with the application of this technique to the study of extreme topography in a near-vertical road cut-slope. Three photogrammetric projects were carried out: one derived from images taken with the camera oriented horizontally, one derived from images taken with the camera tilted at 45°, and one derived from both sets of images. Point clouds and orthophotos were generated for each of these projects. The best accuracies were achieved by the photogrammetric products derived from the combined images set, which had RMSE equal to 0.053 m, 0.070 m and 0.061 m in X, Y and Z direction, respectively. A software program was developed to generate contour lines and cross-sections derived from the point cloud, which was able to represent all terrain geometric characteristics, such as several Z coordinates for a given planimetric (X, Y) point. Furthermore, comparing the contour lines and cross-sections generated from the point cloud using the program developed in this project to those generated from the digital surface model showed that the former are capable of representing geometric terrain characteristics that the latter cannot.

1. Introduction

During the past decade there have been rapid technological developments related to digital elevation modelling. For most of geomorphic applications, topographic surveys have been largely conducted using robotic total stations [1] or differential global navigation satellite systems (GNSS) [2,3]. Nowadays, new technologies, such as terrestrial laser scanning (TLS) [4], aerial laser scanning (ALS) [5,6], and softcopy photogrammetry [7], have improved the accuracy of digital elevation models (DEMs), but they are often time-consuming and costly.

Landforms with complex topography can render these methodologies unusable and even prove dangerous for operators. Furthermore, in the most dynamic environments it is necessary to employ a high temporal frequency of data collection at a very high spatial resolution in order to study their evolution. This is especially necessary when landform evolution may cause both human and economic disaster, as in the case of infrastructure built on these kinds of landforms.

In order to overcome the limitations of traditional techniques, the use of consumer grade cameras mounted on unmanned aerial vehicles (UAVs) to recover terrain information has been the subject of investigation for the past several years [8,9]. UAVs present distinct advantages over conventional piloted aircrafts and satellites, particularly their low cost, operational flexibility, and better spatial and temporal resolution [10,11,12,13]. UAVs require less time than other techniques for data acquisition and, therefore, reduce costs [14]. Moreover, UAV imagery provides results at a resolution and accuracy that cannot currently be met by satellite-derived products [15] and which are very useful in places where the use of other techniques is dangerous. The rapid development of these systems in recent years, and the miniaturization of sensors, have increased the civil applications of UAVs [16]. A detailed description of this evolution and the state of the art can be found in [17], and a review of the applications of UAVs in civil engineering, in general, and in 3D mapping application, in particular, can be found in [18] and [19], respectively.

The integration of computer vision and image analysis has resulted in a technique called structure-from-motion (SfM) [20], which

* Corresponding author.
E-mail addresses: faguera@ual.es (F. Agüera-Vega), carvajal@ual.es (F. Carvajal-Ramírez), pmc824@ual.es (P. Martínez-Carricondo), jusanche@ual.es (J. Sánchez-Hermosilla López), fjmesas@uco.es (F.J. Mesas-Carrascosa), ir1gapoa@uco.es (A. García-Ferrer), 012ppof@uco.es (F.J. Pérez-Porras).

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automatically solves for the geometry of the scene and the camera positions and orientations without the need to specify a priori a network of targets which have known 3D positions [21,22,23]. SfM incorporates multi-view stereopsis (MSV) techniques [24,25], which derives 3D structure from overlapping photography acquired from multiples angles. Lowe [26], Snavely et al. [21], and Forsman et al. [27], applied a scale-invariant feature transform (SIFT) operator for key-point detection for generating 3D point clouds from photographs. Some researchers have concluded that this operator is one of the most robust for large image variations [28,29] [28,29]. SfM with MVS has surpassed the low precision shown by traditional photogrammetric DEMs when compared to airborne LiDAR, as demonstrated by authors who obtained terrain models with centimeter precision and point cloud resolutions that fell between airborne LiDAR and TLS [30]. A more detailed description of SfM can be found in [3,23].

Recent studies have been carried out using UAV imagery and SfM techniques for geomorphologic and terrain mapping purposes. Harwin and Lucieer [11] report accuracies of 0.025–0.040 m in the point cloud of a natural landform generated from UAV imagery and SfM techniques. Lucieer et al. [31] generated a high-resolution Digital Surface Model (DSM) of Antarctic moss beds from UAV imagery obtaining an overall root mean square error (RMSE) of 0.420 m. Mancini et al. [32] studied the creation and validation of point clouds and DSM generated from images of a beach dune system taken by a digital single-lens reflex (DSLR) camera mounted on a rotatory-wing UAV. The UAV-based approach was demonstrated to be straightforward, and the accuracy of the vertical dataset was comparable with results obtained by TLS technology. Lucieer et al. [33] used UAV imagery for mapping landslide displacements. Their DEMs and orthoimages were exported at a resolution of 1 cm resulting in a $RMSE_{XY}$ of 0.070 m and a $RMSE_Z$ of 0.062 m. Tonkin et al. [34] used a rotary-wing UAV to recover images for topographic surveys and they concluded that the DSM produced from the UAV imagery was in good agreement with the total station survey points. Eltner et al. [35] measured surface changes of short-term erosion events using images taken from a rotary-wing UAV; these data were compared to a DSM produced with TLS data, showing that DSMs have an accuracy of less than one centimeter. Mozas-Calvache et al. [36] yielded a methodology based on UAV photogrammetry techniques to study landslide evolution. In their study of a landslide affecting an urban zone, Mateos et al. [37] used techniques combining satellite and UAV images to accurately detect land displacements rates over time.

The work of Clapuyt et al. [9] compared different SfM-derived topography datasets resulting from identical replications and observed, in all cases, measurements precisions on the order of centimeters, demonstrating the reproducibility of UAV-based Earth topography reconstructions based on SfM algorithms.

In [38,39] the influence of several factors (flight altitude, number and of ground control points (GCPs), and terrain morphology) on DSM and orthoimages obtained with UAV photogrammetry, was explored. With a flight altitude of 50 m and 10 GCP, the researches obtained accuracies of 0.053 m in planimetry and 0.049 m in altimetry, but all of the morphologies studied allowed access to any point to take coordinate measurements or perform other related works. Fernández et al. [40] conducted an analysis of landslide evolution by studying the terrain displacements over several years. The terrain morphology and the objective of this work required adapting the usual UAV photogrammetry methodology, using GCPs which were static throughout the duration of the study which was in a complex terrain morphology. Carvajal-Ramírez et al. [41] studied a very complex landslide morphology with inaccessible areas. They only used GCPs located around the study area and compared the accuracies of photogrammetric projects with different images orientations: images oriented orthogonal to the terrain, and classical vertical image orientation. They concluded that the orthogonal image methodology is more appropriate for this kind of morphology.

In summary, there have been great development in UAV photogrammetry in recent years, and it is increasingly used in situations where classical photogrammetry is less efficient or simply not applicable. All of this makes it necessary to continue the development of specific methodologies to obtain accurate results using UAV photogrammetry in extreme situations when classical photogrammetry is not applicable.

This paper provides a methodology to obtain photogrammetrically-derived topographic information from UAV imagery of extreme and dynamic topography, where traditional techniques are dangerous or impossible to apply. Our goals were to quantify the accuracy of the generated point cloud and produce cartographic information for terrains with extreme morphology that is useful for engineers, geologists, and other technicians. In this way, the results obtained in the present work, besides providing knowledge about the geometric accuracy of UAV photogrammetry, will constitute a working methodology that will be useful in civil engineering works that would otherwise be more expensive or impossible to carry out.

2. Study area

The study area covers a cut slope located on the N-340 road, in the province of Almería, southeast Spain, between Almería city and Aguadulce (Fig. 1). The SW and NE rectangle vertices covering the studied area are 540117, 4074712, and 540453, 4074967, respectively (UTM coordinates Zone 30N, European Terrestrial Reference System 1989: ETRS89).

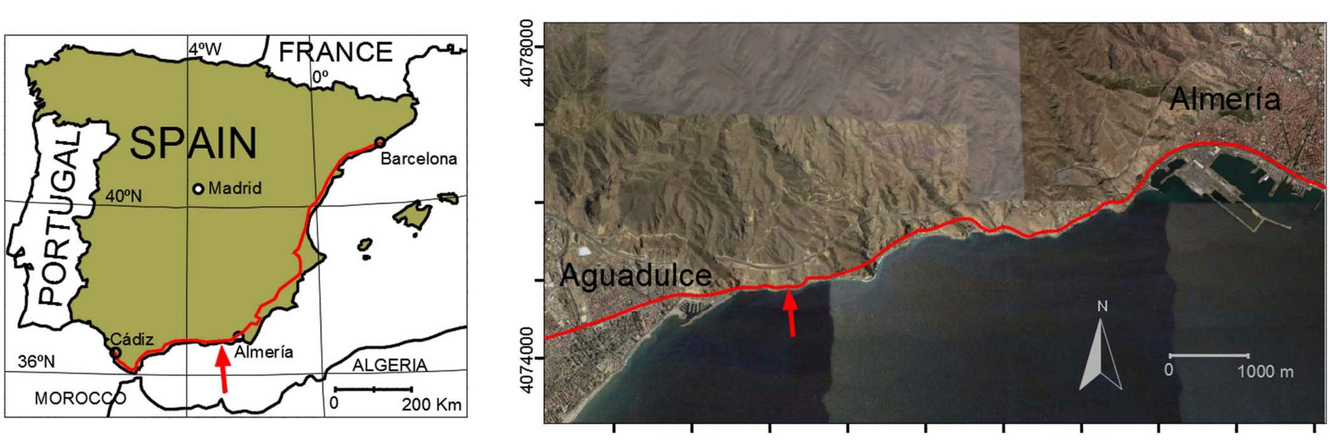

Fig. 1. Geographical location of the study area. The red arrow indicates the location of the study area. The red line represents the N-340 road. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)