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An evaluation of the effectiveness of low-cost UAVs and structure from motion for geomorphic change detection

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ABSTRACT

The measurement of topography and of topographic change is essential for the study of many geomorphic processes. In recent years, structure from motion (SfM) techniques applied to photographs taken by camera-equipped unmanned aerial vehicles (UAVs) has become a powerful new tool for the generation of high resolution topography. The variety of available UAV systems continues to increase rapidly, but it is not clear whether increased UAV sophistication translates into improved quality of the calculated topography. To evaluate the lower end of the UAV spectrum, a simple low cost UAV was deployed to calculate high resolution topography in the Daan River gorge in western Taiwan, a site with a complicated 3D morphology and a wide range of surface types, making it a challenging site for topographic measurement. Terrestrial lidar surveys were conducted in parallel with UAV surveys in both June and November 2014, enabling an assessment of the reliability of the UAV survey to detect geomorphic changes in the range of 30 cm to several meters. A further UAV survey was conducted in June 2015 in order to quantify changes resulting from the 2015 spring monsoon. To evaluate the accuracy of the UAV derived topography, it was compared to terrestrial lidar data collected during the same survey period using the cloud-to-cloud comparison algorithm M3C2. The UAV-generated point clouds match the lidar point clouds well, with RMS errors of 30–40 cm; however, the accuracy of the SfM point clouds depends strongly on the characteristics of the surface being considered, with vegetation, water, and small scale texture causing inaccuracies. The lidar and SfM data yield similar maps of change from June to November 2014, with the same areas of geomorphic change detected by both methods. The SfM-generated change map for November 2014 to June 2015 indicates that the 2015 spring monsoon caused erosion throughout the gorge and highlights the importance of event-driven erosion in the Daan River. The results suggest that even very basic UAVs can yield data suitable for measuring geomorphic change on the scale of a channel reach.

1. Introduction

Topographic change detection is a powerful tool in geomorphology for linking processes and forcings to rates and patterns of erosion and deposition (James et al., 2012). Often applied to studies of processes such as fluvial dynamics (Rumsby et al., 2008; Day et al., 2013; Wheaton et al., 2013), glacial dynamics (Immerzeel et al., 2014; Tonkin et al., 2015), gullying (Marzolff and Poesen, 2009; Perroy et al., 2010), mass wasting (DeLong et al., 2012; Jaboyedoff et al., 2012; Bennett et al., 2013), soil erosion (Rieke-Zapp and Nearing, 2005), and coastal processes (Rosser et al., 2005; Young and Ashford, 2006; Delacourt et al., 2009), this method requires repeated surveys of the area of interest. In order to accurately and effectively measure surface change, these surveys must have sufficient accuracy and precision to resolve changes of the relevant magnitude, must be put into a consistent reference frame so they can be confidently compared, and must be possible to repeat with sufficient frequency to detect changes on the desired timescale. Airborne and terrestrial lidar have emerged in the past 10–15 years as standard tools to quantify geomorphic change, as they allow high resolution measurement at high accuracy and precision (Jaboyedoff et al., 2012). However, despite the quality of the data, lidar has significant drawbacks for the study of change detection. Terrestrial lidar instruments are expensive and in many settings restricted views require scanning from numerous positions to get sufficient coverage. Airborne lidar surveys are very expensive, and while data are becoming increasingly available to the public, frequent repeat surveys or precise temporal coverage are often not feasible. These issues of expense and time can make it difficult to conduct repeat surveys at the desired frequency or to rapidly respond to geomorphic events.

With the recent advances in the use and availability of unmanned aerial vehicle (UAV) platforms and development of easy to use structure from motion (SfM) software, UAV based photogrammetry is increasingly being adopted to produce high resolution topography for the study of surface processes (Colomina and

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Molina, 2014). SfM allows for the generation of topography from randomly oriented and distributed photographs from uncalibrated cameras (Westoby et al., 2012; Fonstad et al., 2013; Smith et al., 2016). Advances in computer vision have resulted in software that can take a set of photographs and calculate both the camera locations and the parameters that describe the camera lenses. This information can then be used to triangulate the locations of points in overlapping photographs and create a cloud of 3D points. For a detailed overview of SfM theory and implementation, see Westoby et al., 2012.

By placing a camera on a UAV, the generation of customized low-altitude aerial photographs has become cheap and easy, and applications requiring repeat surveys at high temporal resolution have become more feasible. This greatly enhances our ability to monitor and quantify rapidly changing landscapes and landscape features. Recent applications have included gully erosion (Gomez-Gutierrez et al., 2014), glacial dynamics (Immerzeel et al., 2014), coastal processes (Delacourt et al., 2013; Gonçalves and Henriques, 2015), landslides (Lucieer et al., 2014; Turner et al., 2015), fluvial dynamics (Miřijovský and Langhammer, 2015), and river bank erosion (Prosdocimi et al., 2015).

UAV systems can vary substantially in price and complexity, but the tradeoffs between these and the quality of the resulting data are not well constrained. I look at one end of this spectrum and evaluate the effectiveness of a simple low cost UAV setup for obtaining high resolution topography in a challenging field setting. The study site is the Daan River gorge in western Taiwan, a rapidly eroding bedrock gorge that has been monitored with terrestrial lidar since 2009. The site presents challenges for the generation and analysis of high resolution topography, including vertical gorge walls, vegetation, wide variation in surface roughness, and a complicated 3D morphology. Both UAV and terrestrial lidar surveys of the gorge were conducted in June 2014 and November 2014, enabling a comparison of the UAV-derived topography to synchronous lidar data. I conducted an additional UAV survey in June 2015, immediately following a series of spring monsoon floods that affected the Daan River.

Accuracy assessment of SfM-derived data has been carried out by a number of previous studies (Harwin and Lucieer, 2012; James and Robson, 2012; Westoby et al., 2012; Fonstad et al., 2013; Tonkin et al., 2014; Smith and Vericat, 2015; Stumpf et al., 2015; Brunier et al., 2016) using terrestrial lidar, airborne lidar, or accurately surveyed ground control points as reference. Most previous studies have assessed accuracy using either the DEM of difference method, which compares DEMs created from the SfM and lidar-derived point clouds, or by comparing the SfM data to independently surveyed points; less common is the direct comparison of point cloud data (e.g. James and Quinton, 2014; Stumpf et al., 2015). Reported accuracies vary widely, from sub-decimeter to over 1 m, reflecting the dependence of SfM accuracy on the ground resolution of the images, in addition to image quality, image distortion, camera calibration, vegetation, surface characteristics, and the number, distribution, and accuracy of ground control points. This study adds to these existing accuracy assessments in several ways. First, it aims to evaluate the most basic possible UAV system to provide constraints on one end-member of the available UAV options. Second, I undertake my surveys in a complicated field setting, enabling me to evaluate the effect of varying surface characteristics on the accuracy of the SfM point cloud. Third, with repeat UAV and terrestrial lidar surveys, both the accuracy of the individual surveys as well as the reliability of the changes detected using SfM can be evaluated. Fourth, I avoid the issues inherent in transforming a point cloud into a DEM and conduct the assessment using a point cloud comparison technique (Lague et al., 2013). This also allows an exploration of the relationships between the characteristics of the raw data and SfM accuracy. Finally, I propose simple methods of evaluating potential errors through reproducibility experiments and of filtering SfM point clouds to remove points with high error.

2. Study site

The Daan River Gorge, located in western Taiwan, is a rapidly eroding bedrock gorge about 1 km long, up to 20 m deep, and 15 to 70 m in width; creating a total elevation range of ~40 m within the study area. The gorge formed in response to surface uplift during the 1999 Mw 7.6 Chi-Chi earthquake, with rapid localized incision that has left the rest of the 400 m wide former river bed largely abandoned (Fig. 1). Since 2009, changes in the gorge have been monitored using repeat terrestrial lidar and kinematic GPS surveys (Cook et al., 2013, 2014). Geomorphic change in the gorge is driven by large typhoon and monsoon floods that cause erosion of gorge walls, the excavation and deposition of coarse sediment within the gorge, and channel avulsions upstream of the gorge accompanied by localized erosion and deposition of up to several meters of coarse sediment.

This site offers the opportunity to compare the performance of UAV-based SfM over a wide range of surface characteristics (Fig. 1). The bedrock in the study area is the Plio-Pleistocene Cholan formation, which consists of interbedded sandstone and mudstone. These layers differ substantially in their resistance to erosion, and in many sections of the gorge differential erosion is reflected in the surface topography. One effect is overhangs at different scales in the wall of the gorge, while another is variable roughness of bare bedrock surfaces depending on bedding orientation and local bedrock properties. Within the gorge, deposition of upstream-derived coarse sediment has created a number of bars, which vary in texture from sand to coarse gravel and boulders. Vegetation in the study area is dominated by silvergrass, which grows extremely rapidly, progressing from isolated plants about 30 cm high to dense stands of grass up to 2 m high over a period of several years. Other vegetation in the study area includes a small number of isolated trees with crowns up to ~2 m in diameter. The abandoned former channel bed contains regions with a range of surface characteristics, including bare smooth bedrock, bare rough bedrock (due to differential erosion where bedding is steeply inclined), sparsely vegetated bedrock, and thickly vegetated alluvial deposits. The different surface characteristics in the study area may affect the accuracy and reliability of SfM based topography.

3. Methods

3.1. UAV system

I use a basic UAV and camera setup, consisting of a manually flown UAV and an independent camera set to take photographs at a fixed interval. The UAV is a DJI Phantom 2 quadcopter flown manually by sight, without waypoint programming or first person view. The cameras used are 16 MP Canon IXUS/Powershot cameras (Powershot 4000IS in June 2014 and IXUS 135 in November 2014 and June 2015), standard point and shoot cameras with 5 mm lenses (28 mm for 35 mm equivalent) and f/3.0 (Powershot 4000) and f/3.2 (IXUS135) apertures at the widest view. The cameras were operated using CHDK (Canon Hack Development Kit), open-source software that adds functionality to select Canon camera models. CHDK allows the camera to be controlled using scripts, such as the script KAP_UAV, which has been developed specifically for aerial photography and enables the camera to take photographs at fixed intervals, in addition to a number of other functions. More information and downloads of CHDK and scripts can be found at http://chdk.wikia.com. The camera was attached to the UAV using a simple homemade camera mount. Vibration from the UAV can lead to blurry images, so an effective camera mount must prevent transmission of vibration to the camera. I achieve this with a mount consisting of two metal plates, one attached to the UAV and one to the camera, with each plate separately anchored in a block of foam such that there is no direct connection from the UAV to the camera (Fig. 2). The total cost for this system is about USD 450. For the June 2015 survey only, I added a communications module to the Phantom 2 that allowed me to program a