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Application of Structure-from-Motion photogrammetry in laboratory flumes

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ABSTRACT

Structure-from-Motion (SfM) photogrammetry has become widely used for topographic data collection in field and laboratory studies. However, the relative performance of SfM against other methods of topographic measurement in a laboratory flume environment has not been systematically evaluated, and there is a general lack of guidelines for SfM application in flume settings. As the use of SfM in laboratory flume settings becomes more widespread, it is increasingly critical to develop an understanding of how to acquire and process SfM data for a given flume size and sediment characteristics. In this study, we: (1) compare the resolution and accuracy of SfM topographic measurements to terrestrial laser scanning (TLS) measurements in laboratory flumes of varying physical dimensions containing sediments of varying grain sizes; (2) explore the effects of different image acquisition protocols and data processing methods on the resolution and accuracy of topographic data derived from SfM techniques; and (3) provide general guidance for image acquisition and processing for SfM applications in laboratory flumes. To investigate the effects of flume size, sediment size, and photo overlap on the density and accuracy of SfM data, we collected topographic data using both TLS and SfM in five flumes with widths ranging from 0.22 to 6.71 m, lengths ranging from 9.14 to 30.48 m, and median sediment sizes ranging from 0.2 to 31 mm. Acquisition time, image overlap, point density, elevation data, and computed roughness parameters were compared to evaluate the performance of SfM against TLS. We also collected images of a pan of gravel where we varied the distance and angle between the camera and sediment in order to explore how photo acquisition affects the ability to capture grain-scale microtopographic features in SfM-derived point clouds. A variety of image combinations and SfM software package settings were also investigated to determine optimal processing techniques. Results from this study suggest that SfM provides topographic data of similar accuracy to TLS, at higher resolution and lower cost. We found that about 100pixels per grain are required to resolve grain-scale topography. We suggest protocols for image acquisition and SfM software settings to achieve best results when using SfM in laboratory settings. In general, convergent imagery, taken from a higher angle, with at least several overlapping images for each desired point in the flume will result in an acceptable point cloud.

1. Introduction

High-resolution topographic data collected during mobile-bed flume experiments has led to important advances in our scientific understanding of fundamental processes in river morphodynamics. For example, differencing successive topographic datasets can be used to quantify the formation and migration of alternate bars (Lisle et al., 1993; Lanzoni, 2000a,b; Venditti et al., 2012), the translation and dispersion of sediment pulses (Sklar et al., 2009; Humphries et al., 2012; Nelson et al., 2015), the formation and migration of meanders (Braudrick et al., 2009; van Dijk et al., 2012), and patterns of bedrock erosion (Johnson and Whipple, 2007; Finnegan et al., 2007). High-resolution topographic data can also provide important information about streambed structure (Aberle and Nikora, 2006), bed roughness, (Qin and Ng, 2012), and bed surface grain size (Butler et al., 2001; Nelson et al., 2010).

It generally is impractical to acquire dense topographic data manually using instruments such as point gages (Gilbert and Murphy, 1914; Brush and Wolman, 1960; Schumm and Khan, 1972). Thus, many modern flumes are outfitted with computer-controlled, mechanized instrumentation carts mounted with laser profilers (Marion et al., 2003; Aberle and Nikora, 2006; Nelson et al., 2010, 2009; Kim et al., 2015) and ultrasonic sensors (Kuhnle, 1993; Venditti et al., 2015). Cart-based measurement systems can be prohibitively expensive

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because such systems are generally highly customized and require high precision instrumentation to maintain accurate positioning during data collection. Terrestrial laser scanning (TLS), while primarily used in field-based applications (Brasington et al., 2012), has been used in some flume settings for comparative studies (Peter Heng et al., 2010; Smith and Vericat, 2014). TLS systems can, however, be extremely expensive and challenging to set up and use.

Digital photogrammetry provides an alternative to TLS or cart-based systems. Traditional close-range digital photogrammetry generally employs the use of multiple cameras to create 3D models of real space. These methods require either the precise location and angle of the camera position or the location of multiple ground control points in each image captured. Traditional photogrammetry has been successfully used in both the field (e.g., Lane et al., 1993; Marzolff and Poesen, 2009) and laboratory (e.g., Chandler et al., 2001; Brasington and Smart, 2003; Stojic et al., 1998; Lane et al., 2001; Bertin et al., 2015). However, the use of these techniques appears to be limited due to the time required to set up such a system and the degree of expertise necessary for accurate reconstruction of a 3D surface (Smith et al., 2015).

An emerging photogrammetric technique that is gaining momentum in the geosciences is Structure-from-Motion (SfM). The concept behind SfM was introduced in the late 1970s (Ullman, 1979), but has risen to popularity among non-photogrammetrists following the work of Snavely et al. (2006). Structure-from-Motion uses multi-view computer vision methods that detect and match features between images to estimate the three-dimensional structure and camera locations and angles simultaneously (Lowe, 2004). There are a number of free software options for SfM processing (e.g., Bundler (Snavely et al., 2006), VisualSFM (Wu et al., 2011; Wu, 2013), and Autodesk ReMake (Autodesk, 2016)) as well as proprietary software (e.g., Arc3D (Tingdahl and Van Gool, 2011) and Agisoft PhotoScan (Agisoft, 2016a)). Compared with other close-range remote sensing techniques such as TLS and more traditional photogrammetry, SfM is relatively low-cost and straightforward to process.

SfM techniques have already been used and tested in a wide array of field applications (e.g., Westoby et al., 2012; Fonstad et al., 2013; Micheletti et al., 2015), but few studies have used SfM in a laboratory setting (Marra et al., 2014; Kasprak et al., 2015; Ramos et al., 2015; Wang et al., 2016). This technology is becoming increasingly popular, but to our knowledge there have been no studies explicitly evaluating the relative performance of SfM against other methods of topographic measurement in a laboratory flume environment (but see Nouwakpo et al. (2014)), and there is a general lack of guidelines for SfM application in flume settings. This is especially problematic because experiments may be conducted in flumes spanning a wide range of physical scales (i.e., widths ranging from a few centimeters to several meters) using sediment ranging from silts or fine sands to large cobbles, and it is not clear how SfM data collection protocols and processing methods should change with flume scale, experimental grain size, or level of detail desired. These issues are all of great interest to experimentalists and therefore the objectives of this study were to: (1) compare the resolution and accuracy of SfM topographic measurements to TLS measurements in laboratory flume experiments of varying scale and grain sizes; (2) explore the effects of different image acquisition protocols and data processing methods on the resolution and accuracy of topographic data derived from SfM techniques; and (3) provide general guidance for image acquisition and processing for SfM applications in laboratory flumes.

2. Methods

For this study, we took advantage of several ongoing flume experiments being conducted at Colorado State University's Engineering Research Center. The flumes used in these experiments have widths varying from 0.22 m to 6.71 m and lengths from 9.14 m to 30.48 m, and the sediment used in the experiments has median grain sizes ranging from 0.20 mm to 31 mm. For each flume, we collected topographic data with two TLS systems, as well as a series of photographs taken at multiple locations with different camera angles that were later used to generate topographic data with SfM. This allowed us to quantitatively compare 3D point clouds generated from each method, and we can explore how the different image acquisition techniques affect topographic data for different flume scales and grain sizes, as well as how SfM processing techniques affect point cloud characteristics. Additionally images were acquired for sediment in a circular pan from a variety of distances and camera angles, for which a qualitative analysis allowed us to assess the requirements necessary to acquire grain-scale topography.

2.1. Flume descriptions

We collected data in five flumes (summarized in Table 1 and shown in Fig. 1a–e), which for this study we refer to with numbers 1 to 5, where the smallest channel is Flume 1 and the largest is Flume 5. We also collected imagery for a pan filled with gravel (Fig. 1f). The grain size distributions of the sediment mixture in each flume and the pan are shown in Fig. 2.

Flume 1 is a narrow (0.22 m wide), 9.14 m long, rectangular channel that is deeper than it is wide (depth = 0.38 m), with a sediment D_{50} of 1.5 mm. This flume has sinusoidal width variations in the downstream direction, and was used in the experiments described in Nelson et al. (2015). At the time of this study, the sediment bed in this flume exhibited riffle-pool topography, with locally high bed elevations in wide sections of the channel (riffles) and locally low elevations in narrow sections (pools).

Flume 2 is 1.22 m wide and 9.14 m long. It was being used to study processes in steep, coarse-grained rivers, and therefore had the coarsest sediment of any of the flumes in this study with a D_{50} of 31 mm.

Flume 3 is 1.22 m wide and 18.29 m long, with a surface sediment D_{50} of 4.1 mm. This flume was being used to investigate alternate bar dynamics, and at the time of data acquisition this flume had approximately 1.5 alternate bar sequences and noticeable bed surface sorting (e.g., Nelson et al., 2010).

Flume 4 is a wide rectangular basin (4.88 m wide by 15.24 m long) that was being used to study flow and erosion around navigation locks. The sediment in this flume was a relatively well sorted (geometric standard deviation $\sigma_g = 1.67$) gravel ($D_{50} = 6.2$ mm).

Flume 5 is a large rectangular basin (6.71 m wide by 30.48 m long) filled with very well sorted ($\sigma_g = 1.37$) sand with $D_{50} = 0.2$ mm. This basin was being used to perform experiments on braided channels in high sediment supply environments (Ettema et al., 2016), and at the time of data acquisition for this study the bed exhibited many shallow (~1 cm depth) braided channels.

The pan is a circular container (0.39 m diameter) filled with a bi-modal mixture of very fine to coarse gravel. This container was not being used for any other experimentation and is only used in this study to examine the effect of camera distance/angle from the sediment surface. No TLS data were collected for the pan because the level of detail of interest is finer than the accuracy of TLS equipment available to us.

2.2. Data acquisition

2.2.1. TLS

Two TLS systems were used to collect topographic data. The first was a Leica ScanStation HDS3000, which is a time-of-flight style scanner with a stated accuracy of ±6 mm at a distance of 50 m (Leica, 2016). This scanner computes distances using the speed of light by measuring the time from short pulses of light sent from the scanner