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Modeling the topography of shallow braided rivers using Structure-from-Motion photogrammetry

L. Javernick [a,*], J. Brasington [b], B. Caruso [a]

[a] Department of Civil and Natural Resources Engineering, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand
[b] School of Geography, Queen Mary, University of London, London E1 4NS, United Kingdom

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ABSTRACT

Recent advances in computer vision and image analysis have led to the development of a novel, fully automated photogrammetric method to generate dense 3d point cloud data. This approach, termed Structure-from-Motion or SfM, requires only limited ground-control and is ideally suited to imagery obtained from low-cost, non-metric cameras acquired either at close-range or using aerial platforms. Terrain models generated using SfM have begun to emerge recently and with a growing spectrum of software now available, there is an urgent need to provide a robust quality assessment of the data products generated using standard field and computational workflows.

To address this demand, we present a detailed error analysis of sub-meter resolution terrain models of two contiguous reaches (1.6 and 1.7 km long) of the braided Ahuriri River, New Zealand, generated using SfM. A six stage methodology is described, involving: i) hand-held image acquisition from an aerial platform, ii) 3d point cloud extraction modeling using Agisoft PhotoScan, iii) georeferencing on a redundant network of GPS-surveyed ground-control points, iv) point cloud filtering to reduce computational demand as well as reduce vegetation noise, v) optical bathymetric modeling of inundated areas; and vi) data fusion and surface modeling to generate sub-meter raster terrain models. Bootstrapped geo-registration as well as extensive distributed GPS and sonar-based bathymetric check-data were used to quantify the quality of the models generated after each processing step.

The results obtained provide the first quantified analysis of SfM applied to model the complex terrain of a braided river. Results indicate that geo-registration errors of 0.04 m (planar) and 0.10 m (elevation) and vertical surface errors of 0.10 m in non-vegetation areas can be achieved from a dataset of photographs taken at 600 m and 800 m above the ground level. These encouraging results suggest that this low-cost, logistically simple method can deliver high quality terrain datasets competitive with those obtained with significantly more expensive laser scanning, and suitable for geomorphic change detection and hydrodynamic modeling.

1. Introduction

During the past decade, advances in survey and sensor technology have created new opportunities to investigate the structure and dynamics of fluvial systems through the development and differencing of high quality digital terrain models for change detection (Wheaton et al., 2010; Brasington et al., 2012) and hydrodynamic numerical model boundary conditions (Williams et al., 2013a). These advances have been delivered through the advent of digital ground-survey technologies, in particular the Global Positioning System (GPS) (Brasington et al., 2000; Wheaton et al., 2013) and perhaps more fundamentally through the emergence of remote survey methods, including softcopy photogrammetry (Lane et al., 2000; Westaway et al., 2003), aerial light detection and ranging (LiDAR) (Charlton et al., 2003; Hilldale and Raff, 2008) and terrestrial laser scanning (TLS) (Brasington et al., 2012; Williams et al., 2013b).

The adoption of these geomatic technologies has driven a profound increase in the dimensionality of topographic datasets and used within river science, and geomorphology more broadly. Traditional cross-section models have been replaced by 2.5-dimensional (2.5d) digital elevation models (DEMs), and more recently by fully 3d point clouds and surface models (Kreylos et al., 2013). However, fluvial terrain modeling remains challenging due to complex topography, partial inundation, and high sediment mobility. These challenges are particularly true for braided rivers and are compounded with large study sites. While the revolutionary power of these geomatic advances has been utilized to develop quality fluvial terrain models, the high hardware and facility costs, and/or labor intensive and lengthy data acquisition limit the extent and frequency of surveys.

Advances in computer vision and image analysis have led to the development of a novel photogrammetric approach called Structure-from-Motion (SfM) that when coupled with Multi-View Stereo (MVS) offers a fully automated method capable of producing high resolution DEMs with low cost consumer grade cameras (Agisoft, 2010; Fonstad et al., 2013). Traditional photogrammetric DEMs were typically less

* Corresponding author. Tel.: +64 212465897.
E-mail address: luke.javernick@pg.canterbury.ac.nz (L. Javernick).

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accurate and precise than airborne LiDAR (Baltsavias, 1999); however, SfM–MVS has produced terrain models with centimeter precision and point cloud resolutions that fall between LiDAR and TLS (Doneus et al., 2011; Fonstad et al., 2013) and has been utilized to accurately model objects on the centimeter to kilometer scale (James and Robson, 2012; Westoby et al., 2012). Recent studies have highlighted the convenience of SfM–MVS by utilizing unmanned or ultralight aircraft (James and Robson, 2012; Dandois and Ellis, 2013) as well as the potential time savings terrestrial image acquisition has over transporting heavy and bulky TLS equipment (James and Robson, 2012).

This paper presents a workflow production combining SfM–MVS, optical-bathymetric mapping, and point cloud filtering that produced three fluvial terrain models of the braided Ahuriri River, New Zealand with 0.5 m resolution and minimal vegetation noise. This workflow offers non-experts a method to produce quality fluvial terrain models with minimal data acquisition costs and moderate (initial surveys) to minimal (repeat surveys) field labor. In contrast to previous studies, this paper provides a rigorous quality assessment of the SfM–MVS performance measured against extensive real time kinematic (RTK)-GPS ground check-datasets for a 102 ha study-reach. To demonstrate the capabilities and limitations of such methods, these methods were extended to evaluate i) a 104 ha contiguous river reach that was comprised of limited quantity and quality geo-control and ii) a 206 ha river reach that was comprised of the two contiguous river reaches' datasets.

1.1. Structure-from-Motion and Multi-View Stereo

Several SfM software packages are currently available. Many, like Microsoft's PhotoSynth, are internet based and allow the user to load images via the internet and process the data remotely without parameter specification. PC based programs such as SFMToolkit and Agisoft's PhotoScan allow the user to set numerous parameters. While it is recognized that PhotoSynth and SFMToolkit are both capable of producing quality DEMs (e.g. James and Robson, 2012; Westoby et al., 2012), this research utilized PhotoScan (version 0.9.0) due to parameter control, user-friendly graphical user interface, inclusive transformation ability, and in part based on the exceptional results published in Doneus et al. (2011).

SfM–MVS generated point clouds are produced in three stages. During the first stage, SfM utilizes supplied photographs and tracking algorithms to identify, match, and monitor the movement of unique features (Verhoeven, 2011; AgiSoft, 2012). Many SfM packages use the Scale Invariant Feature Transform (SIFT) object recognition system (Lowe, 2004) for this process; however, PhotoScan claims to achieve higher alignment quality using custom algorithms that are similar to SIFT (Semyonov, 2011). The second stage determines the camera's intrinsic (focal length, principal point, and lens distortion) and extrinsic (projection center location and the six exterior orientation parameters that define the image) orientation parameters by determining the optimal camera positions through greedy algorithms, and later improves their positions with a bundle-adjustment algorithm (Robertson and Cipolla, 2009; Semyonov, 2011; Verhoeven et al., 2012). In contrast to traditional photogrammetry, SfM does not require the 3d location and orientation of the camera at image capture, nor the 3d location of the control points to be known prior to scene reconstruction (Verhoeven et al., 2012; Westoby et al., 2012). Following the completion of the first two stages, a sparse point cloud has been generated as well as the location and position of every supplied image.

The third stage utilizes the previously determined intrinsic and extrinsic camera locations, a dense multi-view stereo reconstruction (DMVR), and every pixel of the provided images to produce a dense point cloud and a dense surface reconstruction referred to as a *mesh* (AgiSoft, 2012). The resulting dense point cloud is generated in an arbitrary coordinate system; however, PhotoScan can transform the model into the absolute coordinate system provided that a minimum of three ground control points (GCPs) or camera coordinates has been recorded. Transformation through the use of GCPs can be accomplished in the user-interface by manually identifying and marking the GCP object within the imported photographs. Once GCP identification has been completed and the corresponding xyz coordinates have been entered, a linear similarity transformation using seven parameters (three translation, three rotation, and one scaling) is automatically performed. Further, an *optimization* transformation method is also available which utilizes the modeled point cloud and camera parameters to reduce the difference between the model and supplied coordinates (AgiSoft, 2012). However, PhotoScan's transformation algorithms are not fully disclosed and the final resulting point cloud may require user editing due to vegetation and/or additional noise.

1.2. Optical bathymetric mapping

Consistent with other photogrammetric studies, fluvial terrain models generated with SfM–MVS struggle to identify the inundated river bed elevation and thus a significant portion of the terrain remains undocumented. This is unacceptable for most fluvial terrain models due to the river beds' highly active geomorphology (Williams et al., 2011). However, many methods are available to acquire this bathymetric data including remote sensing methods such as bathymetric LiDAR and optical remote sensing (Westaway et al., 2003; Carbonneau et al., 2006; Wedding et al., 2008) as well as field data collection methods using radar, sonar, and RTK-GPS surveys (Brasington et al., 2003; Fonstad and Marcus, 2005; Williams et al., 2011). However, LiDAR methods are expensive and extensive field data collection can be an overwhelming task for large river studies. Thus, optical bathymetric mapping is a practical method to model the river bed elevation at submeter resolution (Marcus and Fonstad, 2008; Williams et al., 2011).

Optical bathymetric mapping requires a correlation between the water's depth and the water's color (Winterbottom and Gilvear, 1997) and works well for shallow water depth and minimal turbidity. To develop a river bed map of the inundated areas, three general steps are taken. First, to develop a relationship between the water's depth and the water's color, near-concurrent aerial photographs and water depth data are assessed. Second, a model of the water surface must be generated. Third, the spatial depth data are subtracted from the corresponding water surface elevation to develop the river bed elevation map. Given that SfM–MVS and optical bathymetric mapping require similar datasets, coupling the two methods to produce a fluvial terrain model is a convenient workflow.

2. Methods

2.1. Workflow

The workflow presented in this paper utilized PhotoScan's SfM–DMVR to generate the terrain surface for dry areas, the geospatial Topographic Point Cloud Analysis Toolkit (ToPCAT; Brasington et al., 2012) to reduce the point cloud resolution to i) improve data handling, and ii) to reduce vegetation noise, and finally optical–empirical bathymetric mapping to model the inundated terrain. The full production (Fig. 1) starts with the acquired aerial photographs, which were utilized in two ways. First, the photographs were uploaded into PhotoScan to produce a georeferenced SfM–DMVR point cloud that was then: i) decimated to reduce the point cloud resolution to a computationally manageable size as well as reduce vegetation noise, ii) utilized to model the dry surface terrain, and iii) used to derive the water surface elevation of the inundated areas. Secondly, PhotoScan utilized the upload photographs to produce mosaicked orthophotos which were: i) utilized with bathymetric data to develop an empirical–optical depth formula, ii) subtract the depth formula from the modeled water surface to obtain a river bed elevation model, and iii) discretize the model into a similar resolution as the SfM point cloud. Finally, the dry and wet point clouds were fused into one point cloud which was utilized to develop the digital elevation model.