Editorial

Low budget topographic surveying comes of age: structure from motion photogrammetry in geography and the geosciences

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I Introduction

Photogrammetry is a technique by which volumetric information describing surface structures can be obtained by exploiting parallax – i.e. the difference in the apparent position of an object, given the varying perspective provided by overlapping images captured from different viewpoints. Structure from motion (SfM) photogrammetry uses advances in computer vision algorithms to implement and expedite the digital photogrammetric workflow. Consequently, SfM photogrammetry can work with un-registered image sets captured from un-calibrated consumer cameras, although users must be mindful of the impacts of camera settings on the quality of resultant data and products (O'Connor et al., 2017). Until quite recently, topographic point cloud data were generally collected and delivered to science users by agencies and organisations with access to high-budget equipment (e.g. laser scanners on board piloted aircraft), and the raw data required powerful computers for data processing. These logistical requirements put such data out of the reach of some users (Westoby et al., 2012). The emergence of SfM photogrammetry as a low cost surveying tool has, in contrast, provided a more democratic means by which scientists can capture and process their own point cloud data, and resultantly, SfM photogrammetry now represents a core data capture and analysis approach within the environmental and geo-sciences disciplines. The paradigm for geospatial surveying is now shifting so that scientists themselves are the data suppliers (Garrett and Anderson, 2018): armed with consumer-grade cameras it is possible to gather data and then process those data using SfM approaches to answer a range of environmental science questions. Applications for SfM photogrammetry to date have included characterisation of forests (Dandois and Ellis, 2010, Zahawi et al., 2015, Mlambo et al., 2017), rivers (Marteau et al., 2017, Woodget et al., 2015), snow (Nolan et al., 2015), and coral reef systems (Leon et al., 2015, Casella et al., 2017), to name just a few. SfM has also been applied to analyse archival image data successfully – e.g. for evaluating dynamism of river floodplains (Bakker and Lane, 2017). However, this new-found route for self-service geospatial and volumetric data is paved with complexities for the user. Data can be captured from ground-based perspectives or from aerial viewpoints (drone and kite platforms facilitate this greatly), and there are a multitude of free, open-source, or commercial software products available with which to process the photographic data into point clouds. Evaluating the quality of the resulting orthomosaics, point clouds and products requires independent data from GNSS or other systems, which may have a much higher unit cost than the equipment used to capture the original photographic data. Implementing the SfM workflow can be computationally expensive for large projects comprising multiple thousands of images, requiring users to have access to high performance computing, or at the very least a powerful desktop with high specification graphics processing unit and large hard disk. Techniques for detailed uncertainty assessment of such data can be memory heavy, and have yet to be widely adopted (James et al., 2017b, Dall'Asta et al., 2015, Murtiyoso et al., 2018).

In this editorial, which introduces a special issue on the topic of SfM photogrammetry in geography and environmental science, we will provide a brief summary of the *status quo* of SfM photogrammetry science, through a lens on published work. We begin by evidencing the rise of SfM photogrammetry work in geography and the geosciences, after which we summarise the main technical advances that have led to this expansion and uptake of the method. We then discuss how SfM photogrammetry has benefited geomorphology and natural hazards research, alongside ecology and hydrology research, throwing a spotlight on the papers contained within this special issue as we proceed.

II The rise of structure from motion photogrammetry within geography and geosciences

Within geographical and environmental science disciplines, there has been a recent upsurge in scholarly work that has developed, applied, evaluated and validated SfM photogrammetry approaches. A SciVal (www.scival.com) literature search on 1 January 2019 (looking for the term "structure from motion" or "structure-from-motion" in the title, abstract or keywords), which returned 605 journal articles and review papers published up to 2018 within the Environmental, Agricultural, Biological, Earth and Planetary sciences, demonstrates the rapid, recent growth in this field (Figure 1).

We draw the reader's attention to several key review papers (Eltner et al., 2016, Bemis et al., 2014) as well as three 'early adopter' papers (Westoby et al., 2012, Fonstad et al., 2013, James and Robson, 2012): each of which provide an excellent starting point from which to understand the technicalities and capabilities of SfM photogrammetry. Recent refinement of technical SfM workflows (Turner et al., 2012, Carbonneau and Dietrich, 2017, James et al., 2017a, James et al., 2017b) has been paralleled by considerable advances in applications, including in spatial ecological (Cunliffe et al., 2016) and geomorphological (Javemick et al., 2014) areas of research, extending to the evaluation of plot-to-landscape scale processes using SfM applied to data acquired from different platforms (Smith and Vericat, 2015). The coincident rise of lightweight drone technology (sometimes referred to as 'unmanned aerial vehicles' (UAVs)) alongside that of SfM photogrammetry has fuelled further the upsurge in interest and use of the technique within natural sciences (Anderson and Gaston, 2013). From these papers, one can get a flavour for the breadth of work within this emerging discipline of self-service, fine spatial resolution surveying.

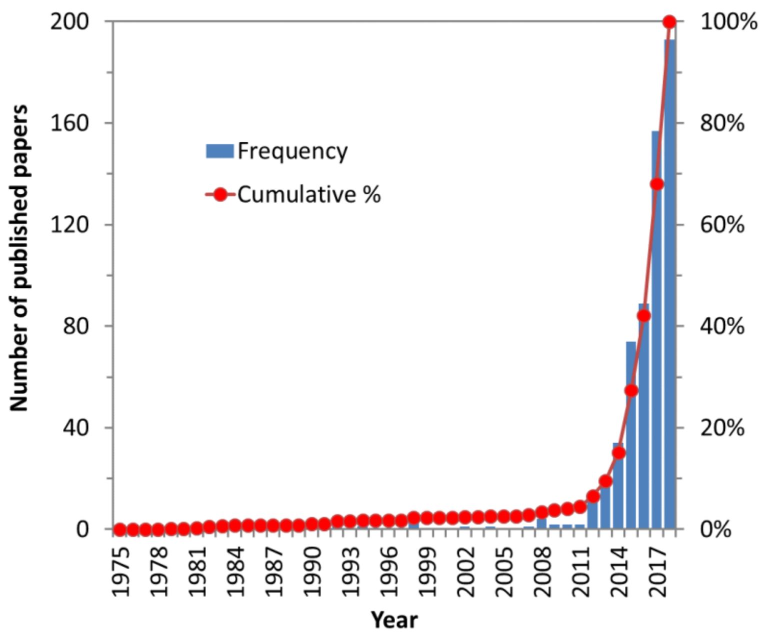

Figure 1: upsurge in papers using structure from motion within the Environmental, Agricultural, Biological, Earth and Planetary sciences. Results are from a SciVal literature search on 1 January 2019, looking for the term "structure from motion" or "structure-from-motion" in the title, abstract or keywords in journal articles and review papers published up to 2018.

III Technical advances

The contribution of SfM-photogrammetry to environmental and geographical research has been supported by advances across image acquisition platforms, cameras and processing software. Research questions have been addressed using image data collected from the ground to space, but aerial views from both piloted platforms (e.g. gyrocopters, parascenders, helicopters and fixed wing aircraft) or unpiloted systems (e.g. kites, rotary or fixed-wing drones) are being increasingly used. In particular, the rapid advances in lightweight drone technology have made data with a combination of centimetric resolution and up to kilometric spatial coverage become widely available.

Drones used for geographical research have evolved from generally bespoke or kit-built systems requiring manual control by an experienced pilot [e.g.(Niethammer et al., 2010)], to off-the-shelf aircraft that are capable of near-autonomous surveying [e.g.(Nakano et al., 2014)]. This transition has enabled image collection to advance from the characteristically irregular acquisition of manually-controlled flights, to being fully autopilot-controlled and GPS-synchronised, following programmed survey designs and flight lines. Simultaneously, image acquisition systems have evolved from typically using consumer cameras individually mounted into airframes (e.g. compact cameras and digital SLRs), to integrated, gimbal-mounted lightweight cameras (e.g. DJI's 1-inch 20-megapixel CMOS sensor; https://www.dji.com/phantom-4-pro) and specialised imaging systems including thermal (e.g. the FLIR Duo Pro thermal sensor for drones; https://www.flir.co.uk/products/duo-pro-r/, and the Workswell WIRIS mini; https://www.workswell-thermal-camera.com/wiris-mini/) and multispectral (E.g. the Parrot Sequoia multispectral sensor) sensors.

Parallel advances have been made in image processing. Initial studies were carried out using early widely-available SfM-based software that was either web-based (e.g. PhotoSynth (Dandois and Ellis, 2010, Stimpson et al., 2010, Rosnell and Honkavaara, 2012, Dowling et al., 2009)), or run on local PCs (e.g. Bundler with patch-based multi-view stereo; (Welty et al., 2010, Niethammer et al., 2010, Castillo et al., 2012, Turner et al., 2012, James et al., 2012). With a heritage in computer science, such software tended to emphasise processing speed over metric accuracy, with aspects such as georeferencing left to external processing. As the broad utility of SfM photogrammetry became apparent, software began to include many more aspects of rigorous photogrammetry, such as integrating georeferencing directly into the workflow (e.g. Agisoft PhotoScan; www.agisoft.com). Drone-focussed software is also now commonly used (e.g. Pix4D (https://www.pix4d.com) and DroneMapper (https://dronemapper.com/) and these can seamlessly integrate survey design, flight planning and image processing, including radiometric considerations for multispectral data.

Following these recent developments in SfM workflows, we see two assessments of techniques within this special issue. Firstly, Griffiths and Burlingham compare the results of processing a salt marsh drone survey with different software and different approaches to camera calibration. Through assessing the resulting systematic error within their model, they show that camera self-calibration can either under-perform or exceed the performance of a pre-calibrated camera model, depending on the software used. Their work underscores some of the complexities involved in SfM-photogrammetry and the importance of carefully designed error checks. Also in this issue, Ratner *et al*. return to the driver behind the early advances in automating SfM by exploring the use of crowd-sourced imagery to generate 3D surface models. Using a volcanic crater as a case study location, they show that data acquired by volunteers walking around the area can be used to generate topographic data suitable for use in disaster risk reduction scenarios.

IV Geomorphology, landscape evolution and natural hazards research

The field of geomorphology has benefited strongly from the emergence of the current generation of SfM tools and associated surveying platforms. The versatility of SfM and the capacity for specialists and non-specialists alike to generate repeat, high-resolution topographic datasets lends itself naturally to geomorphological investigation. Accordingly, uptake by geomorphologists and those working on landscape evolution problems more broadly has been particularly rapid and proactive.

Within the field of fluvial geomorphology, SfM has enabled advances in both fluvial landform and landscape mapping at both the reach (Javemick et al., 2014, Woodget et al., 2015, Dietrich, 2017), landform (Vázquez-Tarrío et al., 2017), and micro-scales such as within experimental flumes (Morgan et al., 2017). SfM datasets have also informed fluvial process analysis; for example, work by Prosdocimi et al. (2017) demonstrates the utility of 4D analysis of SfM datasets for quantifying spatiotemporal patterns of fluvial erosion and deposition using smartphone cameras. Even in the absence of repeat datasets, SfM topography can inform hydrological process analysis; Smith et al. (2014) extracted high water marks from SfM-derived topography and used this information in combination with 2D hydraulic modelling to reconstruct reach-scale peak flow magnitudes in a flash-flood-affected catchment.

In coastal and tidal environments, SfM has been applied to the reconstruction of beach (Brunier et al., 2016), dune (Mancini et al., 2013, Duffy et al., 2018), cliff (James and Robson, 2012, Ružić et al., 2014), and rocky shore platform (Cullen et al., 2018) geomorphic structures. Work on tidal wetlands has shown that the technique can reveal geomorphic features that would be otherwise unresolvable in aerial LiDAR-derived data (Kalacska et al., 2017). Cullen et al. (2018), for example, used SfM-derived models to retrieve the volumes of percussion marks caused by clast abrasion on rocky shore platforms, whilst also advocating for the use of SfM photogrammetry to bridge scale-dependent methodological and observational constraints; a theme which has emerged across disciplines.

The uptake of SfM methods by cryospheric researchers has led to a number of notable advances. Ryan et al. (2015) were among the first to apply SfM photogrammetry to image data acquired from a long-range drone to provide insights into the calving dynamics of a large tidewater glacier at fine spatiotemporal resolution, whilst other notable contributions – for instance, Mallalieu et al. (2017) have pioneered the application of terrestrial SfM for reconstructing ice margin and ice cliff dynamics, providing insights into both the seasonality and spatial variability of glacier surface evolution at the meso-scale. Similarly, Immerzeel et al. (2014) have applied SfM techniques for monitoring dynamics of high-altitude, debris-covered glaciers in the Himalaya, based on drone-captured images. At the micro-scale, work by Kääb et al. (2014) has shed new light on the surface evolution of periglacial sorted circles over multi-annual timeframes.

Some recent studies have also explored the potential for applying SfM methods to archival (predominantly aerial) photosets, and employing 4D analysis to quantify historic landscape evolution, including mountain glacier extent (Midgley and Tonkin, 2017, Mölg and Bolch, 2017) and braided river-floodplain systems (Bakker and Lane, 2017). Quite correctly, many of these studies advocate for the careful consideration of systematic error propagation when applying SfM reconstruction to imagery that has not been acquired with this express purpose in mind.

In this issue, Mather *et al.* compare the utility of archive aerial LiDAR topography and aerial photography, and aerial photography and topographic models acquired through SfM processing of drone-captured photosets for the recognition and automated mapping of periglacial features on an upland site in south-west England. Significantly, the authors develop an integrated approach to landform identification which utilises coarse-spatial resolution image data for landform mapping (<100 m scale), augmented by the use of fine-spatial resolution data for identifying smaller landform elements such as boulders (<1 m). In its broader sense, the work advocates for careful consideration of the appropriate spatial scale of remote sensing-derived image data and topography with respect to the scale of the landscape features under investigation. Also in this issue, Derrien et al. apply SfM photogrammetry to aerial photosets of Piton de la Fournaise, one of the world's most active volcanoes, following a summit collapse in 2007. In an excellent example of the use of SfM to inform hazard exposure at a popular tourist geosite, the authors applied elevation model differencing and 2D feature-tracking respectively to SfM-derived models and orthophotographs of the caldera in 2008 and 2015 to develop a comprehensive picture of mass wasting processes and ground motion across the site. The authors identified retrogressive erosion of the caldera rim caused by the widening of ground fractures, including an increase in widening rates since volcano reactivation in 2014, as well as extensive rock slope deformation and debris avalanche activity. By classifying the wider caldera rim area according to the magnitude and type of ground deformation or mass wasting hazard, and human exposure, the work clearly demonstrates the value of using 4D analysis of repeat SfM topography to inform risk analysis.

V Ecological and hydrological research

Mirroring advances within geological and geomorphological disciplines, ecological and hydrological research has exhibited a similar increase in uptake in the use of SfM photogrammetry approaches. This is because spatial datasets that allow structure/function relationships to be explored have the potential to deliver a step-change in scientific insight within these disciplines.

Within terrestrial vegetation ecology, the pioneering work by Dandois and Ellis (2010) was amongst the first to demonstrate the potential information content of SfM-derived point clouds, demonstrating how fine spatial resolution measurements of vegetation structure could be applied to assessment of biomass, carbon, and in forestry, fire and land management applications. Since this early paper (which utilised their own open-source Ecosynth[1] SfM-based software), there has been a significant adoption of SfM approaches within spatial ecology. There are plentiful examples of SfM being used for tree height inventory for forestry applications (e.g. Birdal et al., 2017) and for estimating stem parameters for timber valuation purposes (e.g. Mikita et al., 2016), as well as for biomass inventory in tropical forests (e.g. Messinger et al., 2016). There has also been considerable exploration of the value of SfM approaches in agricultural settings, for delineating individual trees (Ok and Ozdarici-Ok, 2018, Balsi et al., 2018), for crop height and growth rate estimation in wheat crops (Holman et al., 2016), and for measuring grassland sward height spatial variability (Forsmoo et al., 2018). In shrub-dominated systems where vegetation exhibits a shorter sward, there are also benefits to the SfM approach - Olsoy et al. (2018) demonstrate how SfM point clouds deliver useful information on habitat heterogeneity, and they argue that fine-grained information can improve

[1] http://ecosynth.org/

decision making for informing conservation practices. Working in drylands, Cunliffe et al. (2016), have also demonstrated the application of SfM-derived point clouds for above-ground biomass estimation, whilst a recent study by Webster et al. (2018) pioneered the use of coincident capture and SfM processing of optical and thermal imagery from a UAV to quantify the 4D evolution of forest canopy temperatures. Critically, we note the work of Wallace et al. (2016) who show that in complex forest systems, airborne laser scanning (ALS) may deliver comparatively more accurate estimates of the vertical structure of forests compared to SfM products. However, both Wallace et al. (2016) and Mlambo et al. (2017) comment on the adequacy of SfM products as a lower-cost alternative to ALS for surveying forest stands; which is particularly relevant for those working in remote regions of the world where access to piloted aircraft with ALS equipment is not feasible due to accessibility or cost (Messinger et al., 2016).

Beyond terrestrial ecology, there are recent examples of SfM photogrammetry being implemented in coastal areas, for example, in assessing the climate change impacts of sea level rise on turtle nesting habitat (e.g. using SfM to deliver an accurate fine-grained model of beach topography (Varela et al., 2019)), and for evaluating coral reef structures from both an airborne perspective (e.g. Casella et al., 2017) and from close-range underwater photography (Leon et al., 2015, Burns et al., 2015, Storlazzi et al., 2016).

At the interface of ecology and hydrology, Mercer and Westbrook (2016) have demonstrated the utility of SfM photogrammetry for delivering spatial and volumetric information about complex microform topography, so important in defining the ecohydrological function of complex peatland and wetland systems. In tidal wetlands, a similar relationship exists between eco-morphological structure and hydrological function, and Kalacska et al. (2017) demonstrate successful application of SfM photogrammetry to characterisation of critical hydrological features, including creeks and pond connectivity.

In hydrology, there are also plentiful examples of SfM-derived data being used to deliver new understanding – we refer readers to some of the examples given in section 4. Prosdocimi et al. (2015) showed how SfM-derived elevation models generated using images from a consumer-grade smartphone could deliver a quantitative estimation of deposition and erosion volumes, with reasonable correspondence to those obtained from terrestrial laser scanning (TLS) methods. They extended this method later to measure hydrologically-eroded volumes of soil within a vineyard system with good efficacy (Prosdocimi et al., 2017). Importantly, in the context of erosion studies, Smith and Vericat (2015) urge users to exercise caution when scaling up SfM experiments over larger extents – although some of the errors they highlight can now be mitigated through rigorous methodological steps or accounted for in post-processing using sophisticated error evaluation techniques that are now available (e.g. Monte Carlo point-based uncertainty estimation (James et al., 2017b)). Castillo et al. (2012) and

Glendell et al. (2017) both deliver important work that evidences the cost-effectiveness of SfM erosion estimates over other volumetric surveying techniques.

In this issue, Neverman et al. evaluate results obtained from TLS and SfM photogrammetry surveys captured over an exposed gravel bar in the gravel-bedded Pohangina River, at three points in time, between which the bar had been inundated and re-worked by high flow events, validating the results against *in situ* derived pebble counts. A consumer-grade DJI Phantom drone was used to capture the aerial data used in the SfM workflow. The authors report different relationships between photogrammetry-derived, TLS-derived, and *in situ* observations of grain size distributions, due to the varying geometry of the SfM acquisitions compared to the ground-based oblique-viewing TLS. They also report a bias in the SfM workflow towards sampling of coarser particles, compared to classical *in situ* methods, but conclude by evidencing the various ways in which SfM photogrammetric methods offer other advantages over TLS for such applications (including the "ability to parameterise entrainment and transport rate models for gravel beds by quantifying texture and structure characteristics")

VI Conclusion

SfM photogrammetry approaches have evolved rapidly over the past two decades. At the end of this special issue, Fawcett *et al.* revisit a 'classic' paper by Chandler, published in 1999 which was amongst the first to discuss digital photogrammetry approaches and their potential application within geospatial sciences. Fawcett *et al.* discuss how many of Chandler's early recommendations and insights remain highly relevant within contemporary SfM workflows, whilst also demonstrating the extent to which the field of SfM photogrammetry has evolved since 1999. It is indeed testament to the rapid evolution of SfM photogrammetry that a paper published as recently as 1999 should be considered a 'classic'!

It has been a pleasure to oversee the process of compiling this special issue. The exceptional papers contained herein are testament to the diversity and quality of scientific work now being undertaken across the environmental, ecological and geo-sciences disciplines utilising SfM photogrammetry. We believe that the papers contained herein evidence the establishment of SfM photogrammetry as an operational approach to allow user-derived, quantitative, volumetric (and in some cases, uncertainty-assessed) data to be captured using low-cost sensors. We are not advocates of the view that SfM photogrammetry will *replace* other fine-grained surveying approaches (e.g. terrestrial and airborne laser scanning) by the virtue of SfM delivering a *different type* of data to such approaches. However, the upsurge in SfM photogrammetry's use within the geosciences over the past decades (see Figure 1) is a sign that these techniques will continue to deliver data that complement a wide range of other surveying approaches. We look forward to seeing where SfM photogrammetry takes the disciplines of physical geography and environmental science in the future.

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