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Guidelines on the use of Structure from Motion Photogrammetry in Geomorphic Research

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Abstract

As a topographic modelling technique, structure from motion (SfM) photogrammetry combines the utility of digital photogrammetry with a flexibility and ease of use derived from multi-view computer vision methods. In conjunction with the rapidly increasing availability of imagery particularly from unmanned aerial vehicles, SfM photogrammetry represents a powerful tool for geomorphological research. However, to fully realise this potential, its application must be carefully underpinned by photogrammetric considerations, surveys should be reported in sufficient detail to be repeatable (if practical) and results appropriately assessed to understand fully the potential errors involved. To deliver these goals, robust survey and reporting must be supported through (i) using appropriate survey design, (ii) applying suitable statistics to identify systematic error (bias) and to estimate precision within results, and (iii) propagating uncertainty estimates into the final data products.

Keywords: structure from motion photogrammetry, topographic survey, survey design, systematic error, bias and precision

Introduction

There can be no doubt that structure from motion (SfM) photogrammetry has emerged as one of those once-in-a-generation methodological leaps which transforms practice within a scientific discipline. Geomorphology’s focus upon land surface shape, and its quantification to infer process, to estimate process rates, and to provide information for further analysis (e.g. for the application of landscape evolution models), means that any method able to deliver topographic information both inexpensively and rapidly, is going to have significant appeal. The fractal nature of surface topography (Mark and Aronson, 1984) means that geomorphic process information may be relevant at the sub-millimetre through to the kilometre scale, and this can be implicitly accommodated in photogrammetric measurements by defining the resolution and precision at the scale of interest, through network design (Lane and Chandler, 2003). Early demonstrations of SfM photogrammetry in the geosciences (Fonstad et al., 2013; James and Robson, 2012; Westoby et al., 2012) illustrated that the method differs from previous developments for topographic survey (e.g. terrestrial laser scanning, airborne LiDAR and digital stereo photogrammetry from survey aircraft) because it:

(1) provides a very flexible workflow for robust automatic photogrammetric orientation of networks of images captured from either aerial or terrestrial platforms;

(2) provides flexible and automated camera calibration procedures that are both suited to off-the-shelf consumer-grade cameras and are integrated seamlessly into workflows, further increasing the accessibility of photogrammetry to a wider community;

(3) is implemented within relatively low-cost (sometimes even open or freely available) and user-friendly software, apparently reducing the need for specialist knowledge and skills in the procedures;

(4) can be used with widely available sensor platforms (and associated control software) that are rapidly falling in cost;

(5) and retains the long-standing and fundamental advantage of any photogrammetric approach, that the quality of the results (spatial resolution and precision) is a function of the scale of the imagery acquired.

It is perhaps not surprising, then, that after initial realisation of the potential for SfM photogrammetry in the Earth sciences (Fonstad et al., 2013; James and Robson, 2012; Westoby et al., 2012) and notably through coupling with parallel developments in unmanned airborne vehicles as camera platforms (e.g. Immerzeel et al., 2014; Lucieer et al., 2014; Nakano et al., 2014; Niethammer et al., 2010; Turner et al., 2012; Whitehead et al., 2013), there has been a dramatic increase in the number of publications that make use of this method. Optimal methods for its application have been developed (e.g. Dall'Asta et al., 2015; Harwin et al., 2015; James and Robson, 2014; Wenzel et al., 2013), complementary workflows modified to take advantage of it (e.g. Dietrich, 2017; Woodget et al., 2015) and comparisons made with other approaches (e.g. terrestrial laser scanning; Nouwakpo et al., 2016). As a sign of the power that SfM photogrammetry has for unlocking geomorphic research, it has already been used to address a range of geomorphic questions (e.g. Bertin and Friedrich, 2016; Eltner et al., 2015; Leon et al., 2014; Rippin et al., 2015; Smith and Vericat, 2015; Tonkin et al., 2016). However, most adopters of the method have little or no formal training in photogrammetry. This is not surprising because photogrammetry has traditionally been a specialised method, requiring expensive technology (e.g. metric cameras and digital photogrammetric workstations) and skilled operator expertise, that restricted its accessibility. Furthermore, photogrammetry was primarily (but not exclusively) taught in university engineering or surveying departments, rather than in the geography or geoscience units that typically train geomorphologists. Consequently, many users of SfM photogrammetry have not been exposed to the rigorous approaches and data quality assessments that have been developed over more than half a century of research within the photogrammetry community.

This Commentary, which accompanies a formal editorial statement of the journal Earth Surface Processes and Landforms, is a direct response to the need to ensure that the potential of SfM photogrammetry is fully realised through its correct adoption. There is a direct parallel here with the situation within fluid mechanics in the early 1990s, when computational methods in fluids research started to become popular due to the rapidly increasing availability of high-performance computing (whether through specialised facilities or increasingly powerful desktop computers). As the practical difficulty of applying computing methods was reduced, so a wider range of users adopted the associated technologies, including many who had no training in fundamental numerical methods. To help mitigate against the possibility of publishing research based upon the incorrect use of computational methods and, notably, of numerically inaccurate solutions, recognised academic journals in the field published a series of editorial policy statements (e.g. AIAA, 1994; Freitas, 1993; Roache et al., 1986). This Commentary and the associated editorial policy statement, provide the equivalent for SfM photogrammetry, that is, a set of recommendations and a definition of the benchmark standards required for publication of research which develops or applies SfM photogrammetry in *Earth Surface Processes and Landforms*.

Using and publishing SfM photogrammetry in geomorphology

We provide the following points as guidance for delivering advances in geomorphology through rigorous and reproducible SfM-based measurement, starting with a classification of the contribution style, then proceeding in the order of a typical workflow:

1) *Research contribution:* Papers involving SfM photogrammetry should either apply the method to deliver a clear geoscience-relevant advance, or have a methods or techniques focus and present a demonstrable advance over current measurement practice for surface process understanding. Geoscience-focussed contributions are expected to draw on established photogrammetric survey design principles to deliver data that are ‘fit for purpose’ for answering the science questions posed (i.e. surveys designed to deliver data of sufficient quality and resolution). Methods or technical contributions must be based on sound photogrammetric principles and be broadly applicable, with care taken not to generalise inappropriately. For example, if only a small number of datasets are available, additional evidence may be required to demonstrate findings that are transferable, and to identify the conditions to which those outcomes apply. Case studies that only apply SfM photogrammetry or compare results with other techniques without developing process understanding, or present findings that may be a consequence of the specific data or setting being examined, and where a wider validity is not established, will be considered as reports that, however valid, are not suitable for publication as scientific research papers.
2) *Equipment*: Methods sections should be comprehensive and should include specifications of the sensor used (typically for a camera or cameras, details such as manufacturer and model, sensor size and image size) and the effective focal length and lens type (e.g. zoom or prime lens). For images acquired during sensor motion

(e.g. whilst on a moving UAV), the sensor shutter type (rolling or global) should also be stated, due to the implications for processing with a forward motion correction.

3) *Survey design (image capture)*: Surveys are expected to be designed to acquire data that are suitable for the intended purpose. The survey design should be explained (e.g. for vertical configuration aerial surveys, the nominal flight height, image overlap and ground sampling distance, and for terrestrial and oblique aerial imaging surveys, the image acquisition strategies and ranges of observation distances, degree of convergence etc.), and supported by an appropriate rationale (e.g. to provide a specified data quality over requisite survey extents). Any theoretical error estimates or software used to support survey design should be acknowledged and referenced appropriately.

4) *Survey design (photogrammetric control)*: In almost all cases, some form of control measurements (e.g. scale bars, ground control points, camera positions or orientations) are used to scale and/or georeference survey results. The number and spatial distribution of such control data should be documented, along with the technique and equipment used for control coordinate measurement with its assumed precision and accuracy. Observations that are used as independent check points (rather than as control data) should be clearly identified.

5) *Survey execution*: Any substantial deviation from the survey design (or designs, Points 3 and 4) that arises due to conducting the surveys within uncontrolled field environments should be documented, along with relevant field conditions (e.g. weather and illumination conditions). The overall success of data acquisition should

be described (e.g. the number of images captured, how many were rejected prior to processing and the quality achieved during control and check data survey).

6) *Photogrammetric processing*: The processing software used should be clearly stated (including the version number), and values provided for all relevant processing settings. This should include a statement of the type of camera model used (e.g. normal or fisheye), and documentation of the camera calibration process applied (e.g. which camera model parameters were optimised within any self-calibrating bundle adjustment performed). If multiple independent camera models are used, this should be clear, and which control measurements were included in the bundle adjustment should be stated explicitly. If a pre-calibrated (e.g. semi-metric) camera is used in an SfM photogrammetry framework, the calibrated camera parameters should be given and normally remain fixed during processing. The settings values used for dense image matching and any subsequent processing into products such as digital elevation models, must be provided.

7) *Results (Error reporting)*: The quality of results must be reported. Error metrics should include those that describe bias or accuracy (e.g. mean error; the difference between the average of measurements and the true value) and those that describe precision (e.g. the standard deviation of error); for examples, see Eltner et al. (2016), Hohle and Hohle (2009), and Smith and Vericat (2015). To distinguish clearly between systematic error and random error in geomorphological applications, use of *only* statistics which conflate these two different kinds of error (e.g. Root Mean Square Error, RMSE), should be avoided. Spatial variability of error should be assessed and, by considering systematic error and random error separately, they

can be identified and handled appropriately (e.g. Bakker and Lane, 2017; see Points 11 and 12 below).

8) *Results (images and camera models)*: If appropriate, residual error on image observations and correlation between camera parameters should be explored to provide insight into photogrammetric image network performance. As a minimum, the overall image errors at tie point and control point observations (i.e. in pixels) should be detailed.

9) *Results (control and independent check measurements)*: The quality of photogrammetric results must not be evaluated by simply stating the error observed at control measurements. Any assessment of data quality must involve comparison with *independent* check point coordinates, surfaces or length measurements, or by using a split test (as described below). To assess results for systematic error, the spatial variability of such comparisons should be considered, in addition to providing summary statistics such as mean error or standard deviation of error. The requirement for independent check measurements clearly necessitates that separate datasets are provided for control and check data. In order to generalise overall survey performance for comparisons, results should be non-dimensionalised (e.g. by mean observation distance, survey extent dimensions or nominal ground sampling distance; James and Robson, 2012; Eltner et al. 2016).

10) *Split data tests*: Where no check data are available, attempts should be made to acquire data using a split test. A split test aims to produce two datasets, whether using two different survey designs applied in succession, or the same survey design

on two different dates. Comparison of zones known to be stable should be used to determine the errors likely to be present in the surface model.

11) *Management of systematic error*: Recognising that it is not possible to remove all sources of systematic error, where non-negligible systematic error is identified, it should be either: (a) minimised in subsequent surveys through redesign (see Points 3 and 4); or (b) removed by modelling the error that is present.

12) *Residual uncertainty:* Even with systematic error removed, data will still contain a residual uncertainty, described by its precision statistics. Resultant survey precision should have the same order of magnitude as the theoretical precision of the original design of the survey. If the residual uncertainty is poorer than expected, then this should be analysed and explained, with the spatial distribution of residuals explored.

13) *Data derivatives*: Any analyses of derived products such as dense point clouds or DEMs must not neglect the uncertainties inherent within photogrammetric processing (e.g. the potential for systematic error, as well as the underlying precision of results; James et al., 2017). The implications of surface smoothing or filtering by dense image matching algorithms should be considered when assessing DEM resolutions and derived metrics such as surface roughness or surface change. The consequence of the residual uncertainty of any information that is derived from such data should be determined, whether using simulation (e.g. Monte Carlo based methods) or analytical solutions for the propagation of error (e.g. Taylor, 1997). The latter vary in their sophistication as a function of the assumptions used in their application (e.g. whether errors are pairwise correlated or not; whether errors are Gaussian). Such assumptions should be reported explicitly.

Whilst this guidance is motivated by the increasing use of SfM photogrammetry, the concepts apply to the broader application of photogrammetric approaches within geomorphology, as covered by the associated formal *Earth Surface Processes and Landforms* editorial policy statement.

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