Guidelines on the use of structure-from-motion photogrammetry in geomorphic research

Guidelines on the use of Structure from Motion Photogrammetry

in Geomorphic Research

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1   **Abstract**

2   As a topographic modelling technique, structure from motion (SfM) photogrammetry

3   combines the utility of digital photogrammetry with a flexibility and ease of use derived

4   from multi-view computer vision methods. In conjunction with the rapidly increasing

5   availability of imagery, particularly from unmanned aerial vehicles, SfM photogrammetry

6   represents a powerful tool for geomorphological research. However, to fully realise this

7   potential, its application must be carefully underpinned by photogrammetric

8   considerations, surveys should be reported in sufficient detail to be repeatable (if

9   practical) and results appropriately assessed to understand fully the potential errors

10   involved. To deliver these goals, robust survey and reporting must be supported through

11   the appropriate use of survey design, the application of suitable statistics to identify

12   systematic error (bias) and to estimate precision within results, and the propagation of

13   uncertainty estimates into the final data products.

14

15   **Keywords**: structure from motion photogrammetry, topographic survey, survey design,

16   systematic error, bias and precision

17

18   **Introduction**

19   There can be no doubt that structure from motion (SfM) photogrammetry has emerged

20   as one of those once-in-a-generation methodological leaps which transforms practice

21   within a scientific discipline. Geomorphology's focus upon land surface shape, and its

22   quantification to infer process, to estimate process rates, and to provide information for

23   further analysis (e.g. for the application of landscape evolution models), means that any

24   method able to deliver topographic information both inexpensively and rapidly, is going to

25   have significant appeal. The fractal nature of surface topography (Mark and Aronson,

26   1984) means that geomorphic process information may be relevant at the sub-millimetre

27   through to the kilometre scale, and this can be implicitly accommodated in

28   photogrammetric measurements by defining the resolution and precision at the scale of

29   interest, through network design (Lane and Chandler, 2003). Early demonstrations of

30   SfM photogrammetry in the geosciences (Fonstad et al., 2013; James and Robson,

31   2012; Westoby et al., 2012) illustrated that the method differs from previous

32   developments for topographic survey (e.g. terrestrial laser scanning, airborne LiDAR and

33   digital stereo photogrammetry from survey aircraft) because it:

34   (1) provides a very flexible workflow for robust automatic photogrammetric orientation of

35   networks of images captured from either aerial or terrestrial platforms;

36   (2) provides flexible and automated camera calibration procedures that are both suited to

37   off-the-shelf consumer-grade cameras and are integrated seamlessly into workflows,

38   further increasing the accessibility of photogrammetry to a wider community;

39   (3) is implemented within relatively low-cost (sometimes even open or freely available)

40   and user-friendly software, apparently reducing the need for specialist knowledge and

41   skills in the procedures;

42   (4) can be used with widely available sensor platforms (and associated control software)

43   that are rapidly falling in cost;

44   (5) and retains the long-standing and fundamental advantage of any photogrammetric

45   approach, that the quality of the results (spatial resolution and precision) is a function of

46   the scale of the imagery acquired.

47   It is perhaps not surprising, then, that after initial realisation of the potential for SfM

48   photogrammetry in the Earth sciences (Fonstad et al., 2013; James and Robson, 2012;

49   Westoby et al., 2012) and notably through coupling with parallel developments in

50   unmanned airborne vehicles as camera platforms (e.g. Immerzeel et al., 2014; Lucieer et

51   al., 2014; Nakano et al., 2014; Niethammer et al., 2010; Turner et al., 2012; Whitehead

52   et al., 2013), there has been an dramatic increase in the number of publications that

53   make use of this method. Optimal methods for its application have been developed (e.g.

54   Dall'Asta et al., 2015; Harwin et al., 2015; James and Robson, 2014; Wenzel et al.,

55   2013), complementary workflows modified to take advantage of it (e.g. Dietrich, 2017;

56   Woodget et al., 2015) and comparisons made with other approaches (e.g. terrestrial

57   laser scanning; Nouwakpo et al., 2016).   As a sign of the power that SfM

58   photogrammetry has for unlocking geomorphic research, it has already been used to

59   address a range of geomorphic questions (e.g. Bertin and Friedrich, 2016; Eltner et al.,

60   2015; Leon et al., 2014; Rippin et al., 2015; Smith and Vericat, 2015; Tonkin et al.,

61   2016). However, most adopters of the method have little or no formal training in

62   photogrammetry. This is not surprising because photogrammetry was traditionally a

63   specialised method, requiring expensive technology (e.g. metric cameras, analogue or

64   analytical plotters, or more latterly, digital photogrammetric workstations) and skilled

65   operator expertise, that restricted its accessibility. Furthermore, photogrammetry was

66   primarily (but not exclusively) taught in engineering or surveying university departments,

67   rather than the geography or geoscience units that typically train geomorphologists.

68   Consequently, many users of SfM photogrammetry have not been exposed to the

69   rigorous approaches and data quality assessments that have been developed over more

70   than half a century of research within the photogrammetry community.

71   This Commentary, which accompanies a formal editorial statement of the journal Earth

72   Surface Processes and Landforms, is a direct response to the need to ensure that the

73   potential of SfM photogrammetry is fully realised through its correct adoption. There is a

74   direct parallel here with the situation within fluid mechanics in the early 1990s, when

75   computational methods in fluids research started to become popular due to the rapidly

76   increasing availability of high-performance computing (whether through specialised

77   facilities or increasingly powerful desktop computers). As the practical difficulty of

78   applying computing methods was reduced, so a wider range of users adopted the

79   associated technologies, including many who had no training in the fundamental

80   methods of numerical solution. To help mitigate against the possibility of publishing

81	research based upon the incorrect use of computational methods and, notably, of
82	numerically inaccurate solutions, recognised academic journals in the field published a
83	series of editorial policy statements (e.g. AIAA, 1994; Freitas, 1993; Roache et al.,
84	1986). This Commentary and the associated editorial policy statement, provide the
85	equivalent for SfM photogrammetry, that is, a set of recommendations and a definition of
86	the benchmark standards required for publication of research which develops or applies
87	SfM photogrammetry in *Earth Surface Processes and Landforms*.

88 **Using and publishing SfM photogrammetry in geomorphology**

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

92	1) *Research contribution:* Papers involving SfM photogrammetry should either apply the
93	method to deliver a clear geoscience-relevant advance, or have a methods or
94	techniques focus and present a demonstrable advance over current measurement
95	practice for surface process understanding. Geoscience-focussed contributions are
96	expected to draw on established photogrammetric survey design principles to deliver
97	data that are 'fit for purpose' for answering the science questions posed (i.e. surveys
98	designed to deliver data of sufficient quality and resolution). Methods or technical
99	contributions must be based on sound photogrammetric principles and be broadly
100	applicable, with care taken not to generalise inappropriately. For example, if only a
101	small number of datasets are available, additional evidence may be required to
102	demonstrate findings that are transferable, and to identify the conditions to which
103	those outcomes apply. Case studies that only apply SfM photogrammetry or compare
104	results with other techniques without developing process understanding, or findings
105	that may be a consequence of the specific data or setting being examined, and
106	where a wider validity is not established, will be considered as reports that, however
107	valid, are not suitable for publishing 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 arose 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

134 described (e.g. the number of images captured, how many were rejected prior to

135 processing and the quality achieved during control and check data survey).

136 6) *Photogrammetric processing*: The processing software used should be clearly stated

137 (including the version number), and values provided for all relevant processing

138 settings. This should include a statement of the type of camera model used (e.g.

139 normal or fisheye), and documentation of the camera calibration process applied

140 (e.g. which camera model parameters were optimised within any self-calibrating

141 bundle adjustment performed). If multiple independent camera models are used, this

142 should be clear, and which control measurements were included in the bundle

143 adjustment should be stated explicitly. If a pre-calibrated (e.g. semi-metric) camera is

144 used in an SfM photogrammetry framework, the calibrated camera parameters

145 should be provided and normally remain fixed during processing. The settings values

146 used for dense image matching and any subsequent processing into products such

147 as digital elevation models, must be provided.

148 7) *Results (Error reporting)*: The quality of results must be reported. Error metrics

149 should include those that describe bias or accuracy (e.g. mean error; the difference

150 between the average of measurements and the true value) and those that describe

151 precision (e.g. the standard deviation of error); for examples, see Eltner et al. (2016),

152 Hohle and Hohle (2009), and Smith and Vericat (2015). To distinguish clearly

153 between systematic error and random error in geomorphological applications, use of

154 *only* statistics which conflate these two different kinds of error (e.g. Root Mean

155 Square Error, RMSE), should be avoided. Spatial variability of error should be

156 assessed and, by considering systematic error and random error separately, they

157 can be identified and handled appropriately (e.g. Bakker and Lane, 2017; see Points

158 11 and 12 below).

159 8) *Results (images and camera models)*: If appropriate, residual error on image

160 observations and correlation between camera parameters should be explored to

161   provide insight into photogrammetric image network performance. As a minimum, the

162   overall image errors at tie point and control point observations (i.e. in pixels) should

163   be detailed.

164   9) *Results (control and independent check measurements)*: The quality of

165   photogrammetric results must not be evaluated by simply stating the error observed

166   at control measurements. Any assessment of data quality must involve comparison

167   with *independent* check point coordinates, surfaces or length measurements, or by

168   using a split test (as described below). To assess results for systematic error, the

169   spatial variability of such comparisons should be considered, in addition to providing

170   summary statistics such as mean error or standard deviation of error. The

171   requirement for independent check measurements clearly necessitates that separate

172   datasets are provided for control and check data. In order to generalise overall

173   survey performance for comparisons, results should be non-dimensionalised (e.g. by

174   mean observation distance, survey extent dimensions or nominal ground sampling

175   distance; James and Robson, 2012; Eltner et al. 2016).

176   10) *Split data tests*: Where no check data are available, attempts should be made to

177   acquire data using a split test. A split test aims to produce two datasets, whether

178   using two different survey designs applied in succession, or the same survey design

179   on two different dates. Comparison of zones known to be stable should be used to

180   determine the errors likely to be present in the surface model.

181   11) *Management of systematic error*: Recognising that removing all sources of

182   systematic error is not possible, where non-negligible systematic error is identified, it

183   should be either: (a) minimised in subsequent surveys through redesign (see Points

184   3 and 4); or (b) removed by modelling the error that is present.

185   12) *Residual uncertainty:* Even with systematic error removed, data will still contain a

186   residual uncertainty, described by its precision statistics. Resultant survey precision

187   should have the same order of magnitude as the theoretical precision of the original

188   design of the survey. If the residual uncertainty is poorer than expected, then this

189   should be analysed and explained, with the spatial distribution of residuals explored.

190   13) *Data derivatives*: Any analyses of derived products such as dense point clouds or

191   DEMs must not neglect the uncertainties inherent within photogrammetric processing

192   (e.g. the potential for systematic error, as well as the underlying precision of results;

193   James et al., 2017). The implications of surface smoothing or filtering by dense

194   image matching algorithms should be considered when assessing DEM resolutions

195   and derived metrics such as surface roughness or surface change. The consequence

196   of the residual uncertainty of any information that is derived from such data should be

197   determined, whether using simulation (e.g. Monte Carlo based methods) or analytical

198   solutions for the propagation of error (e.g. Taylor, 1997). The latter vary in their

199   sophistication as a function of the assumptions used in their application (e.g. whether

200   errors are pairwise correlated or not; whether errors are Gaussian). Such

201   assumptions should be reported explicitly.

202   Whilst this guidance is motivated by the increasing use of SfM photogrammetry, the

203   concepts apply to the broader application of photogrammetric approaches within

204   geomorphology, as covered by the associated formal *Earth Surface Processes and*

205   *Landforms* editorial policy statement.

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