Interactive comment on "Image-based surface reconstruction in geomorphometry – merits, limits and developments of a promising tool for geoscientists" by A. Eltner et al.

G. Sofia (Editor)

Received and published: 16 March 2016

Dear Authors, I have now examined the discussion on your paper entitled "Imagebased surface reconstruction in geomorphometry - merits, limits and developments of a promising tool for geoscientists". The two reviewers raised some interesting observations about your research. I agree with both reviewers that the paper was generally well-written and it is comprehensive of the most recent literature. According to the reviewers comments, the manuscript needs a bit of improvement to meet the high quality standards of ESurf. My recommendation follows the ones by the reviewers, to refocus the paper to concentrate on the key developments in the field of SfM through time, and discuss the impact that these developments have had or may have in geomorphometry. You provided interesting replies to the reviewers comments, offering a detailed overview of the steps you are going to take for the review, and i appreciated you submitted also a revised version of the manuscript, with the marked changes. I will consider your revised work with the assistance of the same reviewers who examined the first version of the manuscript. In submitting your revised version, please follow what you already provided in the open discussion, including a detailed list of the changes made to the text, and a detailed list of your responses to each reviewer's comment. Please note that the resubmission does not ensure a final publication in ESurf: a decision will be made only when the revised version will be available, and will be evaluated carefully. Best regards Giulia Sofia

Thank you very much for your comment. We submit the revised version where the changes, we made, are indicated. Furthermore, we include detailed anwers to the referees. We are very grateful for your consideration.

At the end of this file we include the revised manuscript with marked changes that were made in regard to the original manuscript. However, in the answers to the reviewers we refer to the resubmitted manuscript (where tracked changes are excluded).

Interactive comment on "Image-based surface reconstruction in geomorphometry – merits, limits and developments of a promising tool for geoscientists" by A. Eltner et al.

Anonymous Referee #1

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The manuscript by Eltner and co-authors reports a complete review of the Structure from motion applications in geosciences. The manuscript is generally well written and organized. The authors give a general overview of the method describing the main algorithms implemented in the photogrammetric approach. 61 published papers are examined according to their application, divided into seven main topics. Where is provided by the authors, an overview of the obtained accuracies in the examined works is evaluated according to the main source error of the technique and to the error introduced for the accuracy estimation. Further frontiers for the SfM approach are discussed in this paper, highlighting the need of additional investigations on the technique and on the methods to estimate the accuracy, and the need to share a growing amount of data produced by this low cost technique. The Sections describing the accuracy estimation and the source errors could be improved by defining in the text the terms used for the accuracy analysis making it easier to understand and specifying the case studies that are examined for each analysis in order to help the reader for further investigations. The corresponding references could be also included in the description of the SfM applications for each investigated topic.

-We would like to thank the referee for his/her helpful comments, which are very supporting and eventually lead to a significantly improved manuscript. Thank you for your effort and detailed considerations.

Regarding former section 4 (accuracy estimation), we describe used terms more specifically (section 3.2) and include author/case study information to each analysis for clarification (fig. 4-5). This also applies to the former section 3 (SfM applications), which is now section 4 and table 4.

Specific comments

1. I suggest to report in the Section 3 all investigated papers (i.e. authors) for each topic. This could be done adding in the Table A1 a first column with a progressive ID number for each work. Then, for each topic, specify the corresponding ID. For examplep.1455, line 21: ": : : in 7 publications", here, the ID of the relevant papers can be reported, or specify on the Table 2. This is a suggestion. Several published papers provide both a description of the SfM application and an accuracy analysis of the reconstructed object and therefore, it is appropriate to split the considerations about the applications and the accuracies, as done in this review manuscript. However, the Sections 3 (3.1,..., 3.7) should focus mainly on the description of the applications of the method including the authors (see comment before), the object of survey, and the platform used for each corresponding topic. Some applications are missing in the text, and should be provided in order to give a complete view of the main objects surveyed with this technique. To name a few, Woodget et al. (2015) quantified the fluvial topography using hyperspatial resolution UAV imagery and structure from motion photogrammetry; Piermattei et al. (2015) used the SfM for monitoring the mass balance of a debris covered glacier. These applications should be reported in the text.

-Thank you for the suggestion. We add an ID for each publication in Table A1 (appendix) and subsequently provide an additional column in Table 2 (SfM applications) to assign corresponding articles to the relevant topics.

We also include the references provided by the reviewer in the manuscript (table 3).

2. The results of the statistical investigation on the achieved accuracies are reported in the main table (Table A1). Please define the parameter used to evaluate the accuracy also in the text and not only in the caption of the figures. The accuracy parameter named in the paper "measured error" is the standard deviation /RMSE measured in comparison to a reference data (e.g. LiDAR, GPS measurements or with Total station). Please clarify better in the text. Please define how the "superior reference ration" is calculated in the text. As reported in Figure 9 'superior reference ratio' is calculated as ratio between measured error and accuracy of the reference. Please define how the accuracy of the reference data was evaluated. Looking at the Figures about the error analysis (5, 6, 7, 8, 9, 10), a different number of data were plotted, but in the text is reported that 39 case studies provided a value of accuracy estimation. Please specify for each analysis how many case studies were considered and, if possible, report the corresponding references (see comment 1).

-Our apologies; we clearly define each of the accuracy parameters in the revised manuscript. Also, we specify the number of articles and their IDs included in each of the analysis performed (section 3.2.and figure 4 and figure 5).

Technical corrections

p.1448, line 2: 'Early works: : :..mapping (Laussedat, 1899)' Please remove this sentence or move to Section 2.

-Thank you for your comment. However, we would like to keep this very brief historical summary to highlight where photogrammetry and thus also SfM originally evolved from.

p. 1448, line 17: 'to data processing and data acquisition makes it...' It is also the easy data acquisition that increased the number of non-experts users.

-We include both statements in the revised manuscript - the ease of data acquisition and data processing (line 58-59).

p. 1448, line 21: I prefer report the automatism rather than "algorithmic advance". 'that utilizes the high automatism of the SfM algorithm are considered'.

-Thank you for your thought. We change the sentence respectively (line 63).

p. 1448, line 23: 'fully automatic' is not true for all applications and software used as for example the GCPs identification in the images or in the point cloud is still a manual operation in many case. Therefore, I suggest 'semi-automatic' and maybe specifying why: 'The data processing is highly automated and in many software the user-control is limited to some pre-processing step like the manual masking of moving object, the camera calibration parameters setting that can be applied to optimize both accuracy and precision, and the GCPs identification.

-Thank you for the suggestion. We adopt the manuscript according to your comment (line 66). However, we still would like to emphasize the potential of full automation, yet except for scaling/referencing. But even there significant progress has been made, e.g. minimising GCP identification solely to three points due to template matching (as implemented in the SfM-georef tool from James & Robson, 2012) or automatic marker identification due to thresholding (as partly implemented in Agisoft PhotoScan).

p. 1449, line 1-3: Please clarify this sentence. What do you mean with 'a novel point of view'? I suggest to simplify the sentence writing that the SfM characteristics (low-cost and high portability of the instrumentation) allow to increase the temporal analysis of the events but also the spatial analysis thank to the high versatility of the images acquisition. These characteristics and the possibility to acquire images also from aerial platform using UAV increase the applications of the survey method in remote area with limited accessibility and the detection of fast changing environment.

-Thank you for the suggestion. We modify the sentence following the reviewer's advice (line 72-77).

p. 1449, line 23: I suggest to specify the corresponding Section for each point as following: '1. The method... are clarified (Sect. 2); 2. Different field... (Sect.3); 3.... (Section 5); 4. ... (Section6)'. I suggest to move the Section 4 "non commercial software" in the Section 2, especially because at the end of Section 2, p.1453, line10-22, an introduction about the SfM software is provided. Maybe dividing the Section2 in two paragraph, '2.1 : : :: state of art' and '2.2 : : :: tool and data post processing. A brief description also about commercial tool should be described. See comment p.1457-1458.

-Thank you for the suggestion. We add the chapter number to the corresponding objectives in the manuscript. Also, we move section 4 into section 2. However, we mention commercial tools only briefly (line 185-188) due to their usual lack of information about specific algorithmic realisations (black boxes).

p. 1450, line 14. '...usually at least nine homologous points per image' this statement requires a reference.

-Our apologies; we rephrase the entire chapter (section 2.1) to shorten the review, whereby this specific information has been decided to be less relevant and thus is completely deleted from the manuscript.

p. 1450, line 22: the acronym SfM is already described.

-Our apologies; we remove this description.

p. 1451, line 6: I would mentioned also the need to scale the model, as reported also by Snavely at el., 2008, because the SfM estimated the relative position of each camera. To have metric information of the reconstructed surface, in local or global-coordinate system, the ground control points or a scale definition by using a known distance are required to scale and georeference the SfM 3-D model.

-Thank you for the suggestion. We add the further step to scale/geo-reference the model to SfM in a nutshell (line 135).

p.1451, line 25: 'These extrinsic parameters ...' the authors refer to camera position or also intrinsic parameter. Please clarify the sentence.

-Thank you for your comment. However, the entire paragraph is removed to shorten the script. In the revised manuscript we refer to Smith et al. (2015) for further reading (line 136-137).

p. 1452, line 27. Please change 'DSM' with 'DEM'.

-Thank you for the comment. We change it (line 160).

p. 1453, line 10: I suggest mentioning also the commercial software because they are used in the investigated papers.

-Thank you again. However, we prefer to not just yet refer to any software in particular because later on in the manuscript we give more detail about SfM tools. We change the sentence, accordingly (line 170/171).

p. 1453, line 23: I suggest to move the section 4 here, in connection with the paragraph above about the SfM software.

-Thank you for the comment. We follow the reviewer's suggestion (section 2.2).

p. 1454, line 25: Please define the acronym 'LiDAR'.

-Our apologies; we define it (line 278).

p. 1455, line 21: The authors may also want to refer to Ryan et al. (2014).

-Thank for the suggestion. We add this reference from Ryan et al. (2014) on 'Repeat UAV photogrammetry to assess calving front dynamics at a large outlet glacier draining the Greenland Ice Sheet' (Appendix A).

p. 1456, line 19: Ružic et al. (2014) is not mentioned in the bibliography.

-Our apologies; we correct this (line 1290-1292): Ruzic, I., Marovic, I., Benac, C. and Ilic, S.: Coastal cliff geometry derived from structure-from-motion photogrammetry at Stara Baka, Krk Island, Croatia. Geo-Mar. Lett., 34, 555–565. doi:10.1007/s00367-014-0380-4, 2014.

p. 1456, line 20: '... have been retreating up to 5 m since the 1960s: : :' it is not relevant there.

-Thank you for noticing, we remove it.

p. 1456, line 23: An emerging application of SfM is related to snow depth estimation, snow map and rock glacier monitoring. This topic should be reported here, or in the Section 3.3 extended the topic. For example, Fugazza et al. (2015), Dall'Asta et al.(2015).

-Thank you for the suggestions. We add these applications and references (line 391).

p. 1457, line 12: 'Also : : : intervals.' please move this sentence in Section 6.6.

-Thank you for the comment. We follow the reviewer's suggestion (line 835-836).

p. 1457, line 19: Please reorganize Table B1 regarding the software of photogrammetry and cloud processing (if you want to include the latter in this table). Additionally please report both in the text and in the table the free-web service SfM tool, like Photosynth and 123D Catch, especially because they are used in the investigated paper as reported in Table A1 and in Figure 3. In table B 1, I suggest to include also the commercial software adopted in the published papers.

-Thank you for the comment. We include the packages suggested (table 2). However, regarding the tool order, we do not completely understand how the table is supposed to be reorganized because we already ordered it according to SfM tools first and post-processing tools afterwards. Sf3M is listed at the end because it implements both, SfM and post-processing algorithms. Furthermore, in table B1 we would not like to mention commercial software packages due to their black box nature.

p. 1459, line 10: I have my doubts about this statement ': : :the systematic error : : : can be displayed by the mean error values', please support by a reference. As reported by Smith and Quincey (2015), the Mean error values should be treated with caution to estimate the accuracy of SfM reconstruction that often include both positive and negative errors which approximately compensate for each other. Also Dietrich (2015), James and Robson (2014) demonstrated that the systematic error is visible as a pattern of positive and negative differences compared to a reference ground truth data. The effect of this error is principally caused by the parallel geometry of the photographs along the flight lines in case of UAV acquisition and by the radial distortion propagation(Dietrich, 2015) as it is reported in Sect. 5. However this error is not apparent in the mean values, but can be explained by an error distribution map. Perhaps worth a comment in the text.

-Thank you for the comment. We clarify this aspect in the text (line 264-269). We extend the explanation to the fact that of course deviation maps are important, as well. Mean error is not the solely measure for SfM performance evaluation but it is a significant supplement, which is calculated easily.

p. 1459, line 4: I suggest to include this Section in the previous one.

-Thank you for the comment. We move this section accordingly (section 3.1).

p. 1459, line 18: "measured error" please define better what represent this value (See specific comments). I suggest change line 17 to 'In this study, we reported with the term "measured error" the standard deviation or RMS calculated comparing the SfM reconstruction (point cloud, DEM or mesh) with a reference data (i.e. Lidar , total station or GPS measurements)'. Additionally, as reported in the lines 19-25, the GCPs residual error defines an approximate accuracy estimation, especially if the GCPs are including in the BBA. I suppose there is not a big differences by selecting the control point in the model (of course depend on the model resolution) or in the images as is highlighted in your plot (Fig.5). Instead, would be interesting the "measured error" depending on whether the GCPs have been performed in the BBA (one-stage) or after dense matching computation (two-stage).

-Thank you for the thoughts. We change the description regarding measured error to guarantee a better understanding (line 277-279).

Regarding the type of GCP measurement, we do believe there is a quite significant difference between measuring in images, where sub-pixel assignment is possible, and measuring in point clouds, where features are approximated over several points (further depending on the point density). However, comparison with existing studies is difficult because many effects interact. Thus, another study just concentrating on this issue would be interesting.

Considering two- and one-staged BA, we already performed this analysis by using the terms basic and simple SfM tools because their main difference (besides camera calibration) is the implementation of

GCPs. However, we removed the corresponding figure because after reconsidering the information, we think, possible trends are not as obvious.

p. 1460, line 27: '...an increase of distance the measured error decreases', looking at the Figure 5 probably you mean ': : :the measured error increase'. Figure 5 shows more than 39 values (number of case studies that performed the accuracy analysis) probably because it is included all available data from multi-temporal analysis. Please provide the total number of plotted values (See specific comments).

-Thank you for noticing our mistake. We correct this (line 461). Of course, we meant increase. Generally, the measured error tends to increase with distance, and also the error ratio. However, we have explored the reasons behind the departure of some studies from this tendency. We explain the figure in more detail in the revised manuscript, corresponding to the suggestion of the referee, to avoid confusion (caption of figure 5).

p. 1461, line 5: ': : : and at large distance'. Perhaps this sentence requires a reference or an example.

-Thank you for your comment. However, we would like to keep it this way because this sentence refers to observations that can be made (in fig. 5a in the revised manuscript) reviewing the many papers using SfM.

p. 1464, line 3: 'Stumpf et al. (2014) show that higher overlap resolves in better results, even though ground sampling distance decreases due to a smaller focal length.' it is not clear in this sentence the connection with overlap and GSD. Please clarify this sentence.

-Our apologies; we remove the sub-clause regarding GSD due to missing relevance.

p. 1464, line 7: I consider Table 3 not necessary, I suggest to write in the text the number of published applications that use UAV or terrestrial acquisition. I suggest to rewrite this sentence.

-Thank you for the suggestion. We remove the table.

p. 1464, line 25-28. Please clarify the concept. The authors may also want to refer to Wenzel et al. (2013) that explain the relation between the intersection angle and the baseline, the depth accuracy and the image similarity.

-Our apologies; we clarify this by extending the explanation (line 555-558). However, we prefer not to refer to further literature because we believe this geometric principle accounts to basic (photogrammetric) knowledge.

p. 1465, line 11: ': : : 3-D reconstruction: : :' is defined in Table 1 as the three dimensional shape of an object reconstructed from overlapping images, but I suppose here the authors mean the camera geometry reconstruction.

-Thank you for noticing. We actually mean both object reconstruction as well as camera geometry. We correct this in Table 1.

p. 1465, line 12: I suggest to remove the sentence '...because MVS...point cloud'. The MVS algorithm is not the only algorithm used for the dense matching in the investigated papers, and furthermore the image matching computation to generate dense point cloud is mentioned in the next line (line 15: ::).

-Thank you for the comment. However, we do not agree completely. Indeed, we mean MVS because for the dense matching MVS algorithms work/start in the object space with the sparse points (e.g. PMVS), whereas other approaches of dense matching (e.g. stereo matching SGM) work in the image space and do not rely on the sparse point cloud. However, to avoid confusion (and due to lesser relevance) we consent and remove the sentence.

p. 1465, line 24: To estimate the accuracy of the sparse point cloud (tie points) before the dense image-matching computation, a possible solution is to compare the sparse points with an area-based truth data, if this is available. Many software allowed to export the computed tie-points that are used to estimate or refine the camera orientation, and therefore a preliminary accuracy estimation of the SfM reconstruction is performed. This could be explained in the text.

-Thank you for your comment. However, by internal quality control we explicitly do not mean comparison to external references rather than evaluating the image matching e.g. in regard to reprojection error of all tie-points (in pixels). Hence, error assessment would be independent from the reference accuracy and solely the performance of the BA evaluated in regard to image matches. SfM-georef and Sf3M give some information regarding the reprojection error, but are limited to GCPs only. We would like to keep the respective part as it is and solely do a short mention, which can be considered in more detail by consulting the reference, because we believe further explanation would rather cause additional confusion.

p. 1466, line 9: What do the authors mean with'.., if possible, : : :'. I suggest to remove it. Moreover, please provide the number of investigated case studies for the error assessment.

-Our apologies; we rephrase the sentence (line 593).

p. 1466, line 20. I suggest to include the statement of Bemis et al. (2014) about the influence of the duration of the photogrammetric survey on the SfM 3D model quality. He reported that "model quality degrades significantly for durations >30 min".

-Thank you very much for this additional information. We include this information in the manuscript (line 604-607).

p. 1467, line 2: Here, may also provide the statement that by including the control measurements (i.e. GCPs) in the bundle adjustment the error is reduced. Javerinick et al. (2014) provided a reduction of zerror to the decimetre level by including control points in the bundle adjustment.

-Thank you for the suggestion. We include this information regarding Javernick et al. (2014) in the text (line 623/624) and make some further statements regarding the importance of GCPs for correct model estimation in the chapter dealing with the camera calibration because at this point we already made some statements accordingly but missed to state more clearly the importance of GCPs (line 491).

p. 1467, line 16: The authors may also want to refer to Piermattei et al. (2015) in this sentence: '::: be possible (e.g. glacier surface reconstruction, Piermattei et al.,2015)...'.

-Thank you for the suggestion. We include this reference (line 629/630).

p. 1467, line 25: Please include in the text these statements: Bemis et al., (2015) and Smith and Quincey (2015) reported that the control points should be distributed widely across the target area and at the margins, covering a good range of values in each spatial dimension. This is especially true in case of the GCPs are including in the bundle adjustment and the presence of parallel axis camera configuration. Additionally, linear configuration of GCPs should be avoid as reported by Smith and Quincey (2015).

-Thank you for the suggestion. We change the manuscript accordingly (line 636-644). However, regarding the usage of one-staged BA with parallel-axis configuration many literature (e.g. Kraus, 2007) and recommendation exist (due to already long lasting investigations in classical photogrammetry: especially close setup of GCPs around the area of interest as well as height control points in specific distances as a function of image number are relevant). We made some adjustment to the manuscript.

p. 1468, line 1-3: 'Figure 5 illustrates...'. I suggest to report that there is not difference in the measured error of the investigated studies if the GCPs were selected in the pointcloud or in the images. Contrary, white points (i.e. GCPs measured in the images) show higher "measured error" than gray points. However, a limited number of case studies selected the control data in the point cloud. Perhaps report the number.

-Thank you for the suggestion. We include number of studies where GCPs are depicted in point clouds and corresponding IDs (caption of figure 5). However, we would not like to make further statements because there are just too few studies using GCPs in point clouds to detect any trends. Further investigation of GCP measurement for studies under similar conditions would be advisable.

p. 1468, line 19: Please define what the authors mean with 'superior accuracy assessment' and the number of case studies that were considered for this accuracy evaluation (see specific comments).

-Our apologies; we rephrase the sentence for clarification (line 667/668).

p. 1468, line 22: Please change 'scale dependent' with 'to depend from the camera object distance.'

-Our apologies; we change it (line 669/670).

p. 1469, line 7: Please change '3-D reconstructed DEM' with '3D-reconstructed surface' as you explain after, the comparison can be done using the point cloud of the reconstructed surface and not only after the interpolation (DEM). I suggest to report here the necessity of a spatial error distribution for a proper evaluation of systematic error (see comment p. 1459, line 10).

-Thank you for the suggestion. We change it (line 682). Regarding the error distribution, we already made a more detailed description in section 3.1 (as you suggested earlier).

p. 1470, line 11. If the authors want to report these results, please be more quantitative.

-Thank you for the suggestion. We include specific values (line 715/716).

p. 1470, line 12: Please provide the reference of this equation, Fraser (1996), and describe better the component. For example, the standard error is for the x, y, z object coordinates; q is a design factor expressing the strength of the camera network, basically dependent on the angles between intersecting homologous rays; k corresponds to the average number of images at each station; 'D mean distance object-target' probably the authors mean 'camera-object distance'; ': : : (0.29,: : :)' please provide the reference.

-Thank you for the suggestion. However, we already state a reference with the basic principle book by Luhmann et al. (2014). Thank you for noticing the mistake we made regarding object – camera distance. We also add some more information regarding the equations (line 312-315).

p. 1472, line 1-6: Perhaps this statement needs more clarification.

-Thank you for the suggestion. We clarify this (line 744-755).

p. 1474, line 23: The authors may also want to refer to Mulsow et al. (2013) about the time lapse application for monitoring the margin lake, and Whitehead et al. (2014) to use the time-lapse cameras to measuring the daily surface elevation change across anarctic glacier.

-Thank you for the suggestion. However, we do not include Mulsow et al. (2013) because they are using a single camera to track changes of lake levels with time-lapse (as there are many applications in this regard). Also Whitehead et al. (2014) use only a single camera and thus no time-lapse SfM as in James & Robson (2014).

p. 1492, Table 2: I suggest to put the references for each topic. It could be done adding a consecutive ID in the table A1 and reporting here the relative ID in order to help further investigation (see specific comments). This is especially suggested because in each section about the SfM application for each topic not all corresponding papers are described. I think it could be useful write the work/authors for each topic, in the table2 or at the beginning of each paragraph. Some observations about the Table: The last column represents the total number of reviewed papers, please provide a title to this column; the last row is the sum of each column. But if it is like so, probably there is an error in the number: 11(7) rather than 10(7).

-Our apologies; we correct this (table 4).

p. 1493, Table 3: Wrong number of investigated studies '62'. In the text is reported 61publications. Additionally I consider this table not significant.

-Thank you for your comment. We remove this table.

p. 1495, Table A1: Different symbols (comma or dash) are used to separate the values. Please try to be more consistent or specify the differences.

-Thank you for noticing. However, dashes and commas are used differently on purpose if more than one value is reported and should be auto-plausible. We would prefer to leave the table as it is regarding this matter to keep it as short as possible.

p. 1499 Figure 2 is not reported in the text.

-Thank you for the comment, but at chapter 3 figure 2 was mentioned at the end of the first paragraph of the original manuscript.

p. 1500, Figure 3: Wrong number of investigated studies '62'. In the text is reported 61publications.

-Thank you for your comment. We correct the number of reviewed studies (figure 3).

p. 1505, Figure 8: Please specify what represent the different scales in the legend and in the caption. I am assuming that 'scale' refers to the 'camera-object distance'.

-We would like to keep it as it is because we clarify in chapter 5.1.1 the meaning of scale and sensor to surface distance and use both terms separately during the entire manuscript.

p. 1508 Figure 11 is not reported in the text.

-Figure 11 was reported in chapter 7 (conclusion) in the original manuscript. However, in the revised manuscript this figure is implemented at a more convenient position (fig.1 in the revised manuscript, line 59).

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Wenzel, K., Rothermel, M., Fritsch, D. Haala, N., 2013: Image acquisition and model selection for multi-view stereo. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci, pp. 251–258.

Whitehead, K., Moorman, B., & Wainstein, P.: Measuring daily surface elevation and velocity variations across a polythermal arctic glacier using ground-based photogrammetry, Journal of Glaciology, 60(224), 1208-1220, 2014.

Review of 'Image-based surface reconstruction in geomorphometry – merits, limits and developments of a promising tool for geoscientists' by Eltner *et al.*

Matt Westoby

First of all, we would like to thank Matt Westoby for his comprehensive review. It is essential to improve the manuscript, especially regarding the focus of the work. Thank you for your time and important comments.

General comments:

Eltner *et al.* summarise methods, applications and potential future developments of image-based surface reconstruction in the geosciences. The vast majority of the paper is concerned with the most recent incarnation of image-based surface reconstruction, namely 'Structure-from-Motion'. I enjoyed reading the paper – it is generally well-written and is comprehensive, but perhaps a bit on the long side.

However, I have a major concern about the structure and focus of the manuscript. I am left slightly puzzled as to what the paper is trying to be, since it contains large blocks of descriptive text close to the beginning which reads as a manual for SfM/photogrammetry use, which is followed by, essentially, a list of key papers by field, which is in turn followed by an overview of sources of model error, and concludes with a discussion of potential future avenues for future research. I think the structure needs some work, as I struggle to see how it all fits together in its current form.

Thank you for your comment. We reconsider the focus of our work and concentrate stronger on developments regarding SfM performance as well as future avenues. The manuscript has been restructured, accordingly.

Much of the text that describes, in detail, how image-matching and surface reconstruction methods work could be streamlined significantly or removed entirely.

Overviews of the various workflows and methods are already presented in a number of papers, and I don't see much value in repeating these (see for example Smith *et al.* (2015) *Progress in Physical Geography* – doi: 10.1177/0309133315615805). The most interesting text is that which describes the key developments and potential future avenues for research in this field, and how they relate to geomorphology/geomorphometry – I also note that there is no distinction between these two terms.

Thank you for your thought. We shortened the method description significantly and refer to Smith et al. (2015) for more detail (line 136). Solely issues not especially discussed in Smith et al. (2015) regarding the method are left in our manuscript.

My recommendation is to re-focus the paper to concentrate on the key developments in this field through time, and discuss the impact that these developments have had, or may have, on geomorphological and geomorphometric science. There is plenty to write about here and much of which is already done very well in places, but it needs some reorganisation and streamlining. This would constitute a substantial revision.

Please see my specific comments below.

Thank your for the comment. We stronger focus on your suggestions and extended some explanations (entire section 6). However, we believe it will be difficult to hypothise about future trends and would like to keep this to a minimum and rather concentrate on previous key developments and current accomplishments (e.g. table 3).

Specific comments:

Title: Image-based surface topographic reconstruction techniques have been in existence for decades now, with SfM approaches becoming popularised in the last 5 years or so – I think referring to them as 'promising' in the title short-changes what has already been demonstrated – I would argue that we're definitely at a stage now where their potential has been demonstrated, but perhaps not fully realised and applied. I suggest simply changing the title to end '- merits, limits and future developments.'

We change the title according to your suggestion.

The word 'geomorphometry' is not defined. My understanding is that it refers to the science of digital terrain analysis, although the definition has been debated in the literature. Nevertheless, it is worth including somewhere a distinction upfront between 'geomorphology' and 'geomorphometry', which are different things.

Thank you for your thought. We also think clear distinction between both terms is important. However, in the entire article we do not refer to geomorphology explicitly, we only refer to geomorphometry. Thus, we do not think it is necessary to give an extra definition regarding geomorphology but we add a short information regarding the term geomorphometry (line 80/81).

P1447, L6 – I'd use 'three-dimensional' instead. 'Tridimensional' isn't a commonly used term in this field.

We change the word accordingly to 3D (line 19).

P1447, L21 – already two different ways of writing SfM used... Please stick with one longhand and shorthand version throughout – would suggest 'Structure-from-Motion' or 'Structure from Motion' for longhand, and 'SfM' as the shorthand. Also define abbreviations at first usage – should write 'unmanned aerial vehicle', with (UAV) in brackets, and place (SfM) after first usage on line 14 (refer to journal guidelines).

Thank you for noticing. We correct it.

P1448, L22 – initial estimates of what? Presume you mean camera positions, so please make this clear – this early in the paper a layperson won't know what you mean.

Yes, indeed, we missed to clarify this. Thank you for noticing. Indeed, we mean the image network geometry (line 64).

P1448, L26 – you could be more specific here – with suitable ground control, SfM can offer centimetric levels of detail or spatial resolution, for example, and, for reasons of practicality, ground resolution *generally* degrades with increasing areal coverage (i.e. currently tricky to model at centimetric resolution over an area of many square kilometres...)

Thank you for your suggestion. However, we would like to keep the statement as it is due to the following: On the one hand, SfM can offer even higher level of details (even sub-mm) solely depending at the sensor to surface distance (and closest focus distance). On the other hand, the grade of degrading resolution is rather a function of flying height, which of course increases with areal coverage due to practical reasons, and this point is discussed in more detail later in the manuscript. Thus, in the introduction we would like to avoid further explanations.

P1448, L27 – might be useful to explain what you mean by 4D here - three spatial dimensions plus a temporal dimension.

Thank you for noticing. We clarify this in the manuscript by mentioning the temporal dimension (line 71).

P1450, L14 – do you have a reference to support this number of 9 tiepoints per image?

Thank you for your question. However, we rephrased the entire chapter and excluded this information to avoid confusion and concentrate on main issues.

P1450, L22 - no need to define SfM again.

Thank you for noticing. We correct it.

P1453 – Section 3 currently reads much like a list, with scope for much more reference to how the studies you highlight fit within the wider field of geomorphometry.

I actually think that section 3 would work better if placed later on in the paper, after you have introduced non-commercial tools for SfM photogrammetry (section 4), and before section 5 – although see my general comments on this section above. I think it would work better to cover all the

methodological developments from oldest to newest, then showcase existing applications, and then conclude the paper by discussing potential future developments or avenues for research.

Another option might be to weave the various applications in with their associated methodological developments as the paper progresses – you have begun to do this in places – e.g. in section 3.5 you state how Prosdocimi et al. (2015) used smartphone imagery for SfM input – this is an important development (see also Micheletti *et al.* (2015) - *ESPL*) and is a methodological advance which has wider applications beyond just fluvial science.

Thank you for your suggestion. We moved section 3 (now section 4), as you proposed. Regarding section 3 in more detail, we would like to keep our depiction of displayed studies because we try to show these applications that made a step forward, just as you suggest later. However, we conquer that a better presentation would be advisable. Thus, we include a table displaying the key developments and applications that enlarged the view on SfM photogrammetry and also reconsidered our corresponding listing in the manuscript (table 3).

We further restructure section 3 and 5 in the manner that we include a chapter displaying the method on how we got to our conclusions.

P1456, **L16** – strictly speaking, the paper by James and Robson (2012) was the pioneering paper to demonstrate the application of SfM in a coastal setting, not Westoby et al. (2012). I would clarify this.

Thank you for noticing. We rephrased the sentence (line 416-418) to avoid confusion with the work by James & Robson (2012).

P1458, L24 – section 5 – at this point the manuscript reverts again back to a kind of 'user manual' style of writing, which is at odds with the previous section, and doesn't flow very well. This section is very descriptive, and would fit far better into the manuscript as a whole if it focused on the literature which identifies model errors and develops methods to recognise or eliminate them. It seems as though the authors have scrutinised the papers that are summarised in Table A1 and looked at what degree of data quality analysis has been carried out, but in fact it might read better if it was structured in a way that describes how researchers have come to identify and mitigate these errors as SfM usage has increased in recent year. I agree that a full appreciation of the sources of error in the SfM workflow is crucial, but I'm not sure this is the right paper in which to delve into this much detail – indeed, if you expanded this section, there's probably enough material for an entirely separate paper.

Thank you for your comment.

We would like to keep the current structure because we believe to better comprehend and recall errors it is advisable to order them after their sources. However, we moved the error explanation and approach to retrieve the information into an extra methodological chapter (which also contains the application chapter approach, section 3.1). Also, we try to connect better to the application chapter by considering the key developments (table 3).

We believe error evaluation should be considered in this review because we also want to show limits of the method and we believe a detailed description is important to minimise disadvantageous method implementation in the future.

P1471, L21 – I like section 6. To me, this is the most interesting part of the entire paper. I would like to see these sections expanded – they are quite short at present (with the exception of section 6.1), and could be developed much further.

One major development which is not covered is 'direct georeferencing', which entirely removes the requirement for ground control when constructing 3D models which can then be subsequently used for formal, metric analysis – see e.g. Nolan *et al.* (2015) *The Cryosphere*. This technique is mentioned in Figure 11, but does not make an appearance in the text, which I find strange. Direct georeferencing can significantly expand scales and locations of observation since previously inaccessible areas, where establishing a ground control network would be impractical or altogether impossible, could be surveyed. I would request that the authors include this as a new sub-section and discuss its merits and current limitations.

Thank you for your suggestion. We expanded the chapter where possible and included a sub-chapter regarding direct geo-referencing (section 6.8)).

Figures:

Figure 1 – remove 'exemplary' from figure caption.

We remove it.

Figure 5 – is the error ratio in the form '1:XXXX'? Needs labelling. Is 'distance' the distance between camera and object, or scale of the feature or landscape of interest? Not clear at present. There are a total of seven figures concerned with model error statistics. These need combining into one or two multi-panel figures if the authors decide to keep them following revisions to the text.

Thank you for your suggestion. We correct the labels. We certainly will combine figures for better readability and delete some to keep the figures to a minimum (figure 5).

Figure 11 – you mention 'direct referencing', otherwise known as direct georeferencing, in this figure, but I can't find any mention of it in the text. It needs discussing since it is currently one of the most significant developments in the field as it removes the requirement for ground control, thereby expanding the potential scale and types of application.

Thank you for noticing. We discuss direct georeferencing in more detail in the manuscript (section 6.8).

Figure 11 – 'Vehicles'... UAVs, helicopters and boats are all types of vehicle. I think you mean wheeled vehicles (e.g. cars, jeeps etc) – please clarify.

Thank you again. We clarify the types of vehicles.

Image-based surface reconstruction in geomorphometry – merits, limits and developments -of a promising tool for geoscientists

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Abstract

Photogrammetry and geosciences arehave been closely linked since the late 19th century-Today, a wide range of commercial and open source software enable non experts users due to obtainthe acquisition of high-quality 3D datasets of the environment, which was formerly reservedbut it has so far been restricted to a limited range of remote sensing experts, geodesists or owners of specialists because of the considerable cost-intensive_of metric systems for the acquisition and treatment of airborne imaging systems. Complex tridimensionalimagery; Nowadays, a wide range of commercial and open-source software tools enable the generation of 3D and 4D models of complex geomorphological features ean be easily reconstructed from images captured with consumer grade cameras. Furthermore, by geoscientists and other non-experts users. In addition, very recent rapid developments in unmanned aerial vehicle (UAV) technology allow for allows for the flexible generation of high quality aerial surveying and orthophotography generation at a relatively low-cost.

The increasing computing <u>capacitiescapabilities</u> during the last decade, together with the development of high-performance digital sensors and the important software innovations developed by <u>other fields of research (e.g.</u> computer <u>based</u> vision and visual perception)

<u>research fields</u> has extended the rigorous processing of stereoscopic image data to a 3D point cloud generation from a series of non-calibrated images. Structure from motion methods offer algorithms, e.g. robust feature detectors like the scale-invariant feature transform for 2D imagery, which allow(SfM) workflows are based upon algorithms for efficient and automatic orientation of large image sets without further data acquisition information, examples including robust feature detectors like the scale-invariant feature transform for 2D-imagery. Nevertheless, the importance of carrying out <u>correctwell-established</u> fieldwork strategies, using proper camera settings, ground control points and ground truth for understanding the different sources of errors still need to be adapted in the common scientific practice.

This review manuscript-intends not only to summarize the present<u>current</u> state of published researchthe art on structure from motion photogrammetry applications<u>using SfM workflows</u> in geomorphometry, but also to give an overview of terms and fields of application<u>,</u>. Further this article aims to quantify already achieved accuracies and used scales using different strategies, to evaluate possible stagnations of current developments and to identify key future challenges. It is our belief that <u>some lessons learned in already published articles</u>, scientific reports and book chapters concerning the identification of common errors<u>, or</u> "bad practices" and some other valuable information in already published articles, scientific reports and book

1 Introduction

Early works on projective geometries date back to more than five centuries, when scientists derived coordinates of points from several images and investigated the geometry of perspectives. Projective geometry represents the basis for the developments in photogrammetry in the late 19th century, when Aimé Laussedat experimented with terrestrial imagery as well as kites and balloons for obtaining imagery for topographic mapping (Laussedat, 1899). Rapidly, photogrammetry advanced to be an essential tool in geosciences during the last two decades and is lately gaining momentum driven by digital sensors. Simultaneously, growing computing capacities and rapid developments in computer vision leadled to the promising method of Structure from Motion (SfM) that opened the way for low-cost high-resolution topography. Thus, the community using image-based 3D reconstruction experienced a considerable growth, not only in quality and detail of the achieved results but also in the number of potential users from diverse geo-scientific disciplines.

SfM photogrammetry can be performed with images acquired with consumer grade digital cameras and is thus very flexible in its implementation. Its ease of use in regard to data acquisition and processing makes it further interesting to non-experts- (Fig. 1). The diversity of possible applications led to a variety of terms used to describe SfM photogrammetry either from photogrammetric or computer vision standpoint. Thus to avoid ambiguous terminology, a short list of definitions in regard to the reviewed method is given in Table 1. In this review a series of studies that utilise the algorithmic advancesadvance of high automatisation in SfM are considered, i.e. no initial estimates of the image network geometry or user interactions to generate initial estimates are needed. Furthermore, data processing iscan be performed almost fully automatic but. However, some parameter settings, typical for photogrammetric tools₇ (e.g. camera calibration values), can be applied to optimise both accuracy and precision, and GCP or scale identification are still necessary.

SfM photogrammetry can be applied to a vast range of temporal as well as spatial scales and resolutions up to an unprecedented level of detail, allowing for new insights into earth surface processes, i.e. 4D4D (three spatial dimensions and one temporal dimension) reconstruction of environmental dynamics. For instance, the concept of sediment connectivity (Bracken et al., 2014) can be approached from a new perspective through varying time and spacespatio-temporal scales. FurthermoreThereby, the magnitude and frequency of events and their interaction can also be evaluated from a novel point. Furthermore, the versatility of view. Also, the possibility to reconstruct surfaces fromSfM photogrammetry utilising images; captured from aerial or terrestrial perspectives, inherits has the advantage to be being applicable in remote areas with limited access and in fragile-and, fast changing environments.

After the suitability of SfM has been noticed for geo-scientific applications (James and Robson, 2012, Westoby et al., 2012, Fonstad et al., 2013) the number of studies utilising SfM photogrammetry for geomorphometric investigations (thereby referring to the "science of topographic quantification" after Pike et al., 2008) has increased significantly. However, the method needs sophisticated study design and some experience in image acquisition to prevent predictable errors and to ensure good quality of the reconstructed scene. James and Robson (2012Smith et al. (2015) and Micheletti et al. (2015) recommend a setup for efficient data acquisition.

A total of <u>6165</u> publications are reviewed in this study. They are chosen according to the respective field of research and methodology. Only studies are included that make use of the benefits of automatic image matching algorithms and thus apply the various SfM tools.

Studies that lack of full automatisation are excluded, i.e. some traditional photogrammetric software. Topic wise a line is drawn in regard to the term geosciences. The largest fraction of the reviewed articles tackles questions arising in geomorphological contexts. To account for the versatility of SfM photogrammetry, a few studies deal with plant growth on different scales (moss, crops, forest) or investigate rather exotic topics such as stalagmites or reef morphology.

This review aims to highlight the development of SfM photogrammetry as a promisinggreat tool for geoscientists:

- The method of SfM photogrammetry is briefly summarised and algorithmic differences due to their emergence from computer vision as well as photogrammetry are clarified-(section 2).
- (2) Open-source tools regarding SfM photogrammetry are introduced as well as beneficial tools for data post-processing (section 3).
- (2)(3) Different fields of applications where SfM photogrammetry led to new perceptions in geomorphometry are displayed. (section 4).
- (3)(4) The performance of the reviewed method is evaluated. (section 5).
- (4)(5) And frontiers and significance of SfM photogrammetry are discussed- (section 6).

2 SfM photogrammetry: state-of-the-artmethod outline

2.1 Basic concept

Reconstruction of three-dimensional geometries from images has played an important role in the past centuries (Ducher, 1987, Collier, 2002). The production of high-resolution DEMs was and still is one of the main applications of (digital) photogrammetry. Software and hardware developments as well as the increase in computing power in the 1990s and early 2000s made aerial photogrammetric processing of large image datasets accessible to a wider community (e.g. Chandler, 1999).

Camera orientations and positions, which are usually unknown during image acquisition, have to be reconstructed to model a 3D scene. For that purpose, photogrammetry has developed bundle <u>block</u> adjustment (<u>BBABA</u>) techniques, which allowed for simultaneous determination of camera orientation and position parameters as well as 3D object point coordinates for a large number of images- (e.g. Triggs et al, 2000). The input into the <u>BBABA</u> are image coordinates of many tie points, usually at least nine homologous points per image. If the <u>BBABA</u> is extended by a simultaneous calibration option, even the intrinsic camera

parameters can be determined in addition to the extrinsic parameters. Furthermore, a series of ground control points can be used as input into **BBABA** for geo-referencing the image block (e.g. Luhmann et al., 2014, Kraus, 2007, Mikhail et al., 2001).

Parallel developments in computer vision took place that try to reconstruct viewing geometries of image datasets not fulfilling the common prerequisites from digital photogrammetry, i.e. calibrated cameras and initial estimates of the image acquisition scheme. This led to the structure from motion (SfM) technique (Ullman, 1979) allowing to process large datasets and to use a combination of multiple non-metric cameras.

The typical workflow of SfM photogrammetry (e.g. Snavely et al., 2008) comprises the following steps (Fig. 1)::

- identification and matching of homologous image points in overlapping photos (image matching),
- (2) reconstruction of the geometric image acquisition configuration and of the corresponding 3D coordinates of matched image points (sparse point cloud) with iterative <u>BBABA</u>,
- (3) dense matching of the sparse point cloud from reconstructed image network geometry-

Image matching is fully automated in SfM-tools, and different interest operators can be used to select suitable image matching points. One of the most prominent examples for these matching algorithms are both the "scale invariant feature transformation algorithm" (SIFT) and the "Speeded up robust features algorithm" (SURF). In depth descriptions of SIFT and SURF are given by Lowe (1999) and Bay (2008). These algorithms detect features (e.g. Harris corners) that are robust to image scaling, image rotation, changes in perspective and illumination. The detected features are localised in both the spatial and frequency domain and are highly distinctive, which allows differentiating one feature from a large database of other features (Lowe, 2004, Mikolajczyk, 2005). In contrast, kernel based correlation techniques are normally used in photogrammetry, which are more precise (Grün, 2012), but more constrained in regard to image configurations. When applied to oblique imagery, these kernel based correlation techniques are outperformed by the new feature based algorithms especially designed in order to match datasets from unstructured image acquisitions (Grün, 2012).

(4) The information of the positions of the homologous image points is then used to reconstruct the image network geometry, the 3D object point coordinates and the internal camera geometry in an iterative BBA procedure (e.g. Pears et al., 2012). SfM photogrammetry algorithms derive initial scene geometry by a comparatively large number of common features found by the matching algorithms in one pair of images

(Lowe, 2004). These extrinsic parameters are estimated usually using the "random sampling consensus" (RANSAC) – algorithm (Fischler and Bolles, 1981), insensitive to relatively high number of false matches and outliers. This initial estimation of extrinsic parameters is refined in an iterative least-square minimization process, which also optimizes the cameras intrinsic parameters (camera self-calibration) for every single image. In contrast to classical photogrammetry software tools, SfM alsoscaling or georeferencing, which is also performable within step 2.

Smith et al. (2015) give a detailed description of the workflow of SfM photogrammetry, especially regarding step 1 and step 2.

In contrast to classical photogrammetry software tools, SfM allows for reliable processing of a large number of images in rather irregular image acquisition schemes (Snavely et al., 2008) and realises with a much higher degree of process automation. Thus, one of the main differences between usual photogrammetric workflow and SfM is the emphasis on either accuracy or automation, with SfM focusing on the latter (Pierrot-Deseilligny and Clery, 2011). Another deviation between both 3D reconstruction methods is the consideration of GCPs (James and Robson, 2014, Eltner and Schneider, 2015). Photogrammetry performs **BBABA** either one-staged, considering GCPs within the **BBABA**, or two-staged, performing geo-referencing after a relative image network configuration has been estimated (Kraus, 2007). In contrast, SfM is solely performed in the manner of a two-staged BBABA concentrating on the relative orientation in an arbitrary coordinate system. Thus, absolute orientation has to be conducted separately with a seven parameter 3D-Helmerttransformation, i.e. three shifts, three rotations and one scale. This can be done, for instance, with the freeware tool sfm-georef that also gives accuracy information (James and Robson, 2012). Using GCPs has been proven to be relevant for specific geometric image network configurations, as parallel-axes image orientations usual for UAV data, because adverse error propagation can occur due to unfavourable parameter correlation, e.g. resulting in the non-linear error of a DEM dome (Wu, 2014, James and Robson, 2014, Eltner and Schneider, 2015). Within a onestaged **BBABA** these errors are avoided minimised because during the adjustment calculation additional information from GCPs is employed, which is not possible, when relative and absolute orientation are not conducted in one stage.

The resulting oriented image block allows for a subsequent dense matching, measuring many more surface points through spatial intersection to generate a <u>DSMDEM</u> with very high resolution. Recent developments in dense matching allow for resolving object coordinates for

almost every pixel. To estimate 3D coordinates, pixel values are either compared in imagespace in the case of stereo-matching, considering two images, or in the object space in the case of MVS-matching, considering more than two images (Remondino et al., 2014). Furthermore, local or global optimisation functions (Brown et al., 2003) are considered, e.g. to handle ambiguities and occlusion effects between compared pixels (e.g. Pears et al., 2012). To optimise the pixel match<u>matching</u>, (semi-)global constraints consider the entire image or image scan-lines (usually utilised for stereo-matching, Remondino et al.,2014; e.g. semiglobal matching (SGM) after Hirschmüller, 2011), whereas local constraints consider a small area in direct vicinity of the pixel of interest (usually utilised for MVS-matching, Remondino et al., 2014).

SfM photogrammetry software packages are available partially as freeware or even opensource-(e.g. Visual SfM, Bundler or APERO). Most of the packages comprise SfM techniques in order to derive 3D reconstructions from any collection of unordered photographs, without the need of providing camera calibration parameters and high accuracy ground control points. As a consequence, no in-depth knowledge in photogrammetric image processing is required in order to reconstruct geometries from overlapping image collections (James and Robson, 2012, Westoby et al., 2012, Fonstad et al., 2013). But now, also many photogrammetric tools utilise abilities from SfM to derive initial estimates automatically (i.e. automation) and then perform photogrammetric BBABA with the possibility to set weights of parameters for accurate reconstruction performance (i.e. accuracy). In this review studies are considered, which either use straight SfM tools from computer vision or photogrammetric tools implementing SfM algorithms that entail no need for initial estimates in any regard.

Application of 2.2 Tools for SfM photogrammetry and data post processing

SfM methodologies rely inherently on automated processing tools which can be provided by different non-commercial or commercial software packages. Within the commercial approach PhotoScan (Agisoft LLC, Russia), Pix4D (Pix4D SA, Switzerland) and MENCI APS (MENCI Software, Italy) represent complete solutions for 3D photogrammetric processing that have been used in several of the reviewed works.

Initiatives based on non-commercial software have played a significant role in the development of SfM photogrammetry approaches, either 1) open-source, meaning the source code is available with a license for modification and distribution; 2) freely-available, meaning the tool is free to use but no source code is provided or 3) under free web service with no

access to the code, intermediate results or possible secondary data usage (Table 2). The pioneer works by Snavely et al. (2006, 2008) and Furukawa and Ponce (2010) as well as Furukawa et al. (2010) provided the basis to implement one of the first open-source workflows for free SfM photogrammetry combining Bundler and PMVS2/CMVS as in SfMToolkit (Astre, 2015). By 2007, the MicMac project, which is open-source software originally developed for aerial image matching, became available to the public and later evolved to a comprehensive SfM photogrammetry pipeline with further tools such as APERO (Pierrot-Deseilligny and Clery, 2011).

Further contributors put their efforts in offering freely-available solutions based on Graphical User Interfaces (GUI) for SfM photogrammetry (VisualSfM by Wu, 2013) and georeferencing (sfm_georef by James and Robson, 2012). The need for editing large point-cloud entities from 3D reconstruction led to the development of open-source specific tools such as Meshlab (Cignoni et al., 2008) or CloudCompare (Girardeau-Montaut, 2015), also implementing GUIs. Sf3M (Castillo et al., 2015) exploits VisualSfM and sfm_georef and additional CloudCompare command-line capacities for image-based surface reconstruction and subsequent point cloud editing within one GUI tool. Overall, non-commercial applications have provided a wide range of SfM photogrammetry related solutions that are constantly being improved on the basis of collaborative efforts. Commercial software packages are not further displayed due to their usual lack of detailed information regarding applied algorithms and their black box approach.

A variety of tools of SfM photogrammetry (at least 10 different) are used within the differing studies of this review (Fig. 3). Agisoft PhotoScan is by far the most employed software, which is probably due to its ease of use. However, this software is commercial and works after the black box principle, which is in contrast to the second most popular tools Bundler in combination with PMVS or CMVS. The tool APERO in combination with MicMac focuses on accuracy instead of automation (Pierrot-Deseilligny and Clery, 2011), which is different to the former two. The high degree of possible user-software interaction that can be very advantageous to adopt the 3D reconstruction to each specific case study might also be its drawback because further knowledge into the method is required. Only a few studies have used the software in geo-scientific investigations (Bretar, et al., 2013, Stumpf et al., 2014, Ouédraogo et al., 2014, Stöcker et al., 2015, Eltner and Schneider, 2015).

3 Approaches to identify key developments of SfM photogrammetry

The vast recognition of SfM photogrammetry resulted in a large variety of its implementation leading to methodological developments, which have validity beyond its original application. Thus regarding geomorphometric investigations, studies considering field of applications as well as evaluations of the method performance induced key advances for SfM photogrammetry to establish as a standard tool in geosciences (Table 3). In the following, the approaches are introduced concerning the selection and retrieval of scientific papers utilising SfM photogrammetry and methods illustrated concerning integrated consideration of error performance of SfM photogrammetry in geo-scientific studies.

3.1 Selection of scientific papers exploiting SfM photogrammetry

A survey of 6165 scientific papers published between 2012 and 2015 revealedwas conducted, covering a wide range of applications of SfM photogrammetry forin geo-scientific analysis (see Appendix A). The for a detailed list). Common scientific journals, academic databases and standard online searches have been used to search for corresponding publications. Although, it has to be noted that our approach does not guarantee full coverage of the published works using SfM photogrammetry in geosciences. Nevertheless, various disciplines, locations and approaches from all continents are contained in this review (Fig. 2).

To put research hot spots in perspective it should be taken into account that the amount of publications in each discipline is not only dependent on the applicability of the method in that specific field of research. To a greater degree it is closely linked to the overall number of studies, which in the end can probably be broken down to the actual amount of researchers in that branch of science. Relative figures revealing the relation between SfM photogrammetry oriented studies to all studies of a given field of research would be desirable but are beyond the scope of this review.

3.2 Performing error evaluation from recent studies

SfM photogrammetry has been tested under a large variety of environments due to the commensurate novel establishment of the method in geosciences, revealing numerous advantages but also disadvantages regarding to each application. It is important to have method independent references to evaluate 3D reconstruction tools confidently. In total 39 studies are investigated (Table Appendix A), where a reference has been setup, either area

based (e.g. TLS) or point based (e.g. RTK GPS points). Because not all studies perform accuracy assessment with independent references, the number of studies is in contrast to the number of 65 studies that are reviewed in regard to applications.

A designation of error parameters is performed prior to comparing the studies to avoid using ambiguous terms. There is a difference between local surface quality and more systematic errors, i.e. due to referencing and project geometry (James and Robson, 2012). Specifically, error can be assessed in regard to accuracy and precision.

Measurement accuracy, which defines the closeness of the measurement to a reference ideally displays the true surface and can be estimated by the mean error value. However, positive and negative deviations can compensate for each other and thus can impede the recognition of a systematic error (e.g. symmetric tilting) with the mean value. Therefore, numerical and spatial error distribution should also be considered to investigate the quality of the measurement (e.g. Smith et al., 2015). For the evaluation of two DEMs, the iterative closest point (ICP) algorithm can improve the accuracy significantly if a systematic linear error (e.g. shifts, tilts or scale variations) is given, as demonstrated by Micheletti et al. (2014); Nevertheless, this procedure can also induce an error when the scene has changed significantly between the two datasets.

Precision, which defines the repeatability of the measurement, e.g. it indicates how rough an actual planar surface is represented, usually comprises random errors that can be measured with the standard deviation or RMSE. However, precision is not independent from systematic errors. In this study, the focus lies on RMSE or standard deviation calculated to a given reference (e.g. to a LiDAR point cloud) and thus the general term "measured error" is used.

Furthermore, error ratios are calculated to compare SfM photogrammetry performance between different studies under varying data acquisition and processing conditions. Thereby, the relative error (e_r) , the reference superiority (e_s) and the theoretical error ratio (e_t) are considered. The first is defined as the ratio between measured error and surface to camera distance (eq. 1).

$$e_r = \frac{\sigma_m}{D}$$

(1)

<u>Being:</u> $e_r \dots relative \ error$ $\sigma_m \dots measured \ error$ $D \dots mean \ distance \ camera - surface$ The reference superiority displays the ratio between the measured error and the error of the reference (eq. 2). It depicts the validity of the reference to be accountable as a reliable dataset for comparison.

$$e_s = \frac{\sigma_m}{\sigma_{ref}} \tag{2}$$

Being:

 $e_r \dots reference$ superiority $\sigma_{ref} \dots reference$ error

The theoretical error ratio includes the theoretical error, which is an estimate of the theoretically best achievable photogrammetric performance under ideal conditions. It is calculated separately for convergent and parallel-axes image acquisition schemes. The estimate of the theoretical error of depth measurement for the parallel-axis case is displayed by eq. 3 (more detail in Kraus, 2007). The error is determined for a stereo-image pair and thus might overestimate the error for multi-view reconstruction. Basically, the error is influenced by the focal length, the camera to surface distance and the distance between the images of the stereo-pair (base).

$$\sigma_p = \frac{D^2}{Bc} \sigma_i \tag{3}$$

Being:

 σ_p ... coordinate error for parallel – axes case c ... focal length σ_i ... error image measurement <u>B... distance between images (base)</u>

For the convergent case the error also considers the camera to surface distance and the focal length. However, instead of the base the strength of image configuration determined by the angle between intersecting homologous rays is integrated and additionally the employed number of images is accounted for (eq. 4; more detail in Luhmann et al., 2014).

$$\sigma_c = \frac{q_D}{\sqrt{k}c}\sigma_i$$

(4)

Being:

σ_c ... coordinate error for convergent case q ... strength of image configuration, i.e. convergence k ... number of images

Finally, the theoretical error ratio is calculated displaying the relation between the measured error and the theoretical error (eq. 5). The value depicts the performance of SfM photogrammetry in regard to the expected accuracy.

$$e_t = \frac{\sigma_m}{\sigma_{theo}} \tag{5}$$

<u>Being:</u> $e_t \dots theoretical error <u>ratio</u>$ $\sigma_{theo} \dots theoretical error; eihter <math>\sigma_p$ or σ_c

The statistical analysis of the achieved precisions of the reviewed studies is performed with the Python Data Analysis Library (pandas). If several errors are given in one study due testing of different survey or processing conditions, the error value representing the enhancement of the SfM performance has been chosen, i.e. in the study of Javernick et al. (2014) the DEM without an error dome, of Rippin et al. (2015) the linear corrected DEM, and of Eltner & Schneider (2015) the DEMs calculated with undistorted images. In addition, if several approaches are conducted to retrieve the deviations value to the reference, the more reliable error measure is preferred (regards Stumpf et al., 2014 and Gómez-Gutiérrez et al., 2014 and 2015). Apart from those considerations, measured errors have been averaged if several values are reported in one study, i.e. concerning multi-temporal assessments or consideration of multiple surfaces with similar characteristics, but not for the case of different tested SfM tools. Regarding data visualisation, outliers that complicated plot drawing, were neglected within the concerning graphics. This concerned the study of Dietrich (2016) due to a very large scale of an investigated river reach (excluded from Fig. 4a and Fig. 5a-b), the study of Snapir et al. (2014) due to a very high reference accuracy of Lego bricks (excluded from Fig. 4c and Fig. 5b), and Frankl et al. (2015) due to a high measured error as the study focus was rather on feasibility than accuracy (excluded from Fig. 5c).

Besides exploiting a reference to estimate the performance of the 3D reconstruction, registration residuals of GCPs resulting from BA can be taken into account for a first error assessment. But it is not suitable as exclusive error measure due to potential deviations

between the true surface and the calculated statistical and geometric model, which are not detectable with the GCP error vectors alone because BA is optimised to minimise the error at these positions. However, if BA has been performed two-staged (i.e. SfM and referencing calculated separately), the residual vector provides reliable quality information because registration points are not integrated into model estimation.

4 Recent applications of SfM photogrammetry in geosciences

<u>The</u> previously described advantages of the method <u>introducehas introduced</u> a new group of users, leading to a variety of new studies in geomorphic surface reconstruction and analysis. Different disciplines started to use SfM algorithms more or less simultaneously. <u>It should be noted that common scientific journals</u>, databases and standard online searches do not guarantee complete coverage of all studies about SfM photogrammetry in geosciences. Nevertheless, various disciplines, locations and approaches from all continents are contained in this review (Fig. 2).

A list of all topics reviewed in this manuscript according to their year of appearance is shown in Table 24. It is important to note that most subjects are not strictly separable from each other: For instance, a heavy flash flood event will likely trigger heavy damage by soil erosion or upstream slope failures. Thus, corresponding studies are arranged in regard to their major focus. The topic soil science comprises studies of soil erosion as well as soil microtopography.

To put research hot spots in perspective it should be taken into account, that the number of publications from each discipline is not only dependent on the applicability of the method in that specific field of research. To a greater degree it is closely linked to the overall number of studies, which in the end can probably be broken down to the actual amount of researchers in that branch of science. Relative figures revealing the relation between SfM photogrammetry oriented studies to all studies of a given field of research would be desirable but are beyond the scope of this review.

3

4.1 Soil science

An identification of convergent research topics of SfM photogrammetry in geosciences revealed a distinct focus on erosional processes, especially in soil erosion (11 studies). Gullies, as often unvegetated and morphologically complex features of soil erosion, are

predestined to serve as a research object (6 studies) to evaluate SfM photogrammetry performance. One of the first works on SfM in geosciences from 2012 compared established 2D and 3D field methods for assessing gully erosion (e.g. light detection and ranging - LiDAR, profile meter, total station) to SfM photogrammetry withdatawith regard to costs, accuracy and effectiveness revealing the superiority of SfM photogrammetrythe method (Castillo et al., 2012). Also for a gully system, Stöcker et al. (2015) demonstrated the flexibility of SfM photogrammetry bycamera based surface reconstructionby combining independently captured terrestrial images with reconstructed surface models from UAV images to fill data gaps and achieve a comprehensive 3D model. Another advantage of SfM photogrammetry - surface measurement of large Large areal coverage withand very high resolution - allowed for a new quality in the assessment of plot based soil erosion analysis (Eltner et al., 2015)

Another 6 studies tackle the 3D reconstruction of soil micro-topography by producing very dense point clouds or DEMs. This data further serves to assess pros and cons of SfM photogrammetry, e.g. with regard to the doming effect (Eltner and Schneider, 2015), to detect small-scale erosion features (Nouwakpo et al., 2014), with regard to the doming effect (Eltner and Schneider, 2015) or as input parameter for erosion modelling (Kaiser et al., 2015).

34.2 Volcanology

Volcanology is a pioneering area of SfM photogrammetry research in geosciences because 3 out of 6 studies in 2012 included volcanic research sites. James and Robson (2012) acquired information on volcanic dome volume and structural variability prior to an explosion from multi-temporal imagery taken from a light airplane. Brotheland et al. (2015) also surveyed volcanic dome dynamics with airborne imagery, but at larger scale for a resurgent dome. Another interesting work by Bretar et al. (2013) successfully reveals roughness differences in volcanic surfaces from lapilli deposits to slabby pahoehoe lava.

34.3 Glaciology

Glaciology and associated moraines are examined in 7 publications. Rippin et al. (2015) present a fascinating UAV based work on supra-glacial runoff networks, comparing the drainage system to surface roughness and surface reflectance measurements and detecting linkages between all three. In several UAV campaigns Immerzeel et al. (2014) detected limited mass losses and low surface velocities but high local variations of melt rates that are linked to supra-glacial ponds and ice cliffs. Rippin et al. (2015) present another UAV-based work on supra-glacial runoff networks, comparing the drainage system to surface roughness

and surface reflectance measurements and detecting linkages between all three. Furthermore, snow depth estimation and rock glacier monitoring are increasingly performed with SfM photogrammetry (Nolan et al., 2015, Dall'Asta et al., 2015).

34.4 Mass movements

Compared to the well-stablished use of LiDAR techniques on the investigation of landslides (Jaboyedoff et al., 2012) the use of photogrammetric workflows for investigating hazardous slopes is still scarce, wich is probably due to the stringent accuracy and safety requirements.For instance, the use of UAV systems for monitoring mass movements using both image correlation algorithms and DM substraction techniques has been explored by Lucieer et al., (2013). More recently, SfM techniques were monitoredused by Stumpf et al. (2014) at afor monitoring landslide- displacements and erosion during several measuring campaigns, including the study of seasonal dynamics on the landslide body, superficial deformation and rock fall occurrence. In addition, thes authors assessed the accuracy of two different_3D reconstruction tools were tested and compared to LiDAR data. –Furthermore, seasonal dynamics of the landslide body and different processes, like lobes and rock fall, eould be separated.

34.5 Fluvial morphology

Channel networks in floodplains were surveyed by Prosdocimi et al. (2015) in order to analyse eroded channelschannel banks and to quantify the transported material. Besides classic DSLR cameras, evaluation of an iPhone camera revealed sufficient accuracy, so that in near future also farmersnon-scientist are able to carry out post event documentation of damage. An interesting large scale riverscape assessment is presented by Dietrich (2016), who carried out a helicopter based data acquisition of a 32 km river segment. A small helicopter proves to close the gap between unmanned platforms and commercial aerial photography from airplanes.

34.6 Coastal morphology

In the pioneering article by Westoby et al. (2012) several morphological features of contrasting landscapes where chosen to test the capabilities of SfM; one of them being a coastal cliff of roughly 80 m height. Up to 90.000 points/m² enabled the identification of bedrock faulting. Ružić et al. (2014) produced surface models of coastal cliffs that have been retreating up to 5 m since the 1960s to test the abilities of SfM photogrammetry in undercuts and complex morphologies.

3.7 Others

4.7 Other fields of investigation in geosciences

In addition to the prevalent fields of attention also more exotic research is carried out unveiling unexpected possibilities for SfM photogrammetry. Besides the benefit for the specific research itself, these branches are important as they either explore new frontiers in geomorphometry or demonstrate the versatility of the method. Lucieer et al. (2014) analyse artic moss beds and their health conditions by using high-resolution surface topography (2 cm DEM) to simulate water availability from snow melt. Leon et al. (2015) acquired underwater imagery of a coral reef to produce a DEM with a resolution of 1 mm for roughness estimation. Genchi et al. (2015) used UAV-image data of an urban cliff structure to identify bio erosion features and found a pattern in preferential locations.

The re-consideration of historical aerial images is another interesting opportunity arising from the new algorithmic image matching developments that allow for new DEM resolutions and thus possible new insights into landscape evolution (Gomez et al., 2015). <u>Also accounting for the temporal scale, completely new insights can be achieved by time lapse analysis, already demonstrated by James and Robson (2014b), who monitored a lava flow at minute intervals.</u>

3 Non-commercial tools for SfM photogrammetry and data post-processing

Initiatives based on non-commercial software have played a significant role in the development of SfM photogrammetry approaches, either open-source, meaning the source code is available with a license for modification and distribution, or freely-available, meaning the tool is free to use but no source code is provided (Appendix B). The pioneer works by Snavely et al. (2006, 2008) and Furukawa and Ponce (2010) as well as Furukawa et al. (2010) provided the basis to implement one of the first open source workflows for free SfM photogrammetry combining Bundler and PMVS2/CMVS as in SfMToolkit (Astre, 2015). By 2007, the MicMac project, which is open-source software originally developed for aerial image matching, became available to the public and later evolved to a comprehensive SfM photogrammetry pipeline with further tools such as APERO (Pierrot Deseilligny and Clery, 2011).

Further contributors put their efforts in offering freely-available solutions based on Graphical User Interfaces (GUI) for image-based 3D reconstruction (VisualSfM by Wu, 2013) and georeferencing (sfm_georef by James and Robson, 2012). The need for editing large point-cloud entities from 3D reconstruction led to the development of open-source specific tools such as Meshlab (Cignoni et al., 2008) or CloudCompare (Girardeau-Montaut, 2015), also implementing GUIs. Sf3M (Castillo et al., 2015) exploits VisualSfM and sfm_georef and additional CloudCompare command-line capacities for image-based surface reconstruction and subsequent point cloud editing within one GUI tool. Overall, non-commercial applications have provided to date a wide range of SfM photogrammetry related solutions that are constantly being improved on the basis of collaborative efforts.

A variety of tools of SfM photogrammetry (at least 10 different) are used within the differing studies of this review (Fig. 3). Agisoft PhotoScan is by far the most employed software, which is probably due to its ease of use. However, this software is commercial and works after the black box principle, which is in contrast to the second most popular tools Bundler in combination with PMVS or CMVS. The tool APERO in combination with MicMae focuses on accuracy instead of automation (Pierrot-Deseilligny and Clery, 2011), which is different to the former two. The high degree of possible user software interaction that can be very advantageous to adopt the 3D reconstruction to each specific case study might also be its drawback because further knowledge into the method is required. Only a few studies have used the software in geo-scientific investigations (Bretar, et al., 2013, Stumpf et al., 2014, Ouédraogo et al., 2014, Stöcker et al., 2015, Eltner and Schneider, 2015).

4 Performance of SfM photogrammetry in geo-scientific applications

It is important to have method independent references to evaluate 3D reconstruction tools confidently. This time, 39 studies are investigated (Table Appendix A), where a reference has been setup, either area based (e.g. TLS) or point based (e.g. RTK GPS points). Because not all studies perform accuracy assessment with independent references, the number of studies is in contrast to the number of 61 studies that were reviewed in regard to applications in Sect. 3.

5.1 Error terms

A definite designation of error parameters is performed prior to comparing the studies to avoid using ambiguous terms. There is a difference between local surface quality and more systematic errors, i.e. due to referencing and project geometry (James and Robson, 2012). Specifically, error can be assessed in regard to accuracy and precision.

Accuracy defines the closeness of the measurement to the true surface and usually implies systematic errors, which can be displayed by the mean error value. For the evaluation of two

DEMs, the iterative closest point (ICP) algorithm can improve the accuracy significantly if a systematic linear error (e.g. shifts, tilts or scale variations) is given, as demonstrated by Micheletti et al. (2014).

Precision defines the repeatability of the measurement, e.g. it indicates how rough an actual planar surface is represented. Precision usually comprises random errors and is measured with the standard deviation or RMSE. However, precision is not independent from systematic errors. In this study, focus lies on precision which also might be influenced by systematic errors and thus the general term "measured error" is used.

Registration residuals of GCPs resulting from BBA allow for a first error assessment. But it is not sufficient as exclusive error measure due to potential deviations between the true surface and the calculated statistical and geometric model, which are not detectable with the GCP error vectors alone because BBA is optimised to minimise the error at these positions. However, if BBA has been performed two-staged (i.e. SfM and referencing calculated separately), the residual vector provides reliable quality information because registration points are not integrated into model estimation.

Further

5 Error assessment of SfM photogrammetry in geo-scientific applications

Error evaluation in this study is performed with reference measurements. Thereby, errors due the performance of the method itself and errors due to the method of quality assessment have to be distinguished.

5.21 Error sources of image-based 3D reconstruction SfM photogrammetry

The error of 3D reconstruction is influenced by many factors: scale/distance, camera calibration, image network geometry, image matching performance, surface texture and lighting conditions, and GCP characteristics, which are examined in detail in this section. The statistical analysis of the achieved accuracies of the reviewed studies is performed with the Python Data Analysis Library (panda). If several errors were measured with the same setup, e.g. in the case of multi-temporal assessments, the average value is applied. Furthermore, outliers that complicated data visualisation, were neglected within the concerning plots. This concerned the study of Dietrich (2016) due to a large scale, the study of Snapir et al. (2014) due to a high reference accuracy and Frankl et al. (2015) due to a high measured error.

Scale and sensor to surface distance

SfM photogrammetry contains the advantage to be useable at almost any scale. Thus, in the reviewed studies the method is applied at a large range of scales (Fig. 4_a), reaching from 10 cm for volcanic bombs (Favalli et al., 2012, James and Robson, 2012) up to 10 km for a river reach (Dietrich, 2016). Median scale amounts about 100 m. SfM photogrammetry reveals a scale dependent practicability (Smith and Vericat, 2015) if case study specific tolerable errors are considered, e.g. for multi-temporal assessments. For instance, at plot and hillslope scale 3D reconstruction is a very sufficient method for soil erosion studies, even outperforming TLS (Nouwakpo et al., 2015, Eltner et al., 2015, Smith and Vericat, 2013), whereas error behaviour is not as advantageous for larger scales, i.e. catchments (Smith and Vericat, 2015).

Besides scale, observation of the distance between sensor and surface is important for imagebased reconstructed DEM error, also because scale and distance interrelate. The comparison of the reviewed studies indicates that with an increase of distance the measured error decreases, which is not unexpected (Fig. 5<u>a</u>, circles). However, there is no linear trend detectable. Therefore, <u>a uniform error ratio (orthe</u> relative error), which is calculated by dividing distance with measured error, is not assignable. The <u>relative</u> error-ratio itself displays a large range from 15 to 4000 with a median of 400, thus revealing a rather low error potential (Fig. 5<u>a</u>, triangles). Very high ratios are solely observable for very close-range applications and at large distances. A general increase of the <u>relative</u> error ratio with distance is observable (Fig. 5<u>a</u>, triangles). The indication that cm-accurate measurements are realisable at distances below 200 m (Stumpf et al., 2014) can be confirmed by Fig. 5<u>a</u> because most deviations are below 10 cm until that range. Overall, absolute error values are low at close ranges, whereas the <u>relative</u> error-ratio is higher at larger distances.

Camera calibration

SfM photogrammetry allows for straight forward handling of camera options due to integrated self-calibration, but knowledge about some basic parameters is necessary to avoid unwanted error propagation into the final DEM from insufficiently estimated camera models. The autofocus as well as automatic camera stabilisation options should be deactivated if a pre-calibrated camera model is used or one camera model is estimated for the entire image block because changes in the interior camera geometry due to camera movement cannot be captured with these settings. The estimation of a single camera model for one image block is usually preferable, if a single camera has been used, whose interior geometry is temporary stable, to

avoid over parameterisation (Pierrot-Deseilligny and Clery, 2011). Thus, if zoom lenses are moved a lot during data acquisition, they should be avoided due to their instable geometry (Shortis et al., 2006, Sanz-Ablanedo et al., 2010) that impedes usage of pre-calibrated fixed or single camera models. A good compromise between camera stability, sensor size and equipment weight, which is more relevant for UAV applications, are achieved by compact system cameras (Eltner and Schneider, 2015). However, solely three studies utilize compact system cameras in the reviewed studies (Tonkin et al., 2014, Eltner and Schneider, 2015, Eltner et al., 2015).

Along with camera settings, the complexity in regard to the considered parameters of the defined camera model within the 3D reconstruction tool is relevant, i.e. as well as the implementation of GCPs to function as further observation in the BA, i.e. to avoid DEM domes as a consequence of insufficient image distortion estimation (James and Robson, 2014, Eltner and Schneider, 2015). Also, Stumpf et al. (2014) detect worse distortion correction with a basic SfM tool, considering a simple camera model, compared to more complex software, integrating a variety of camera models- and GCP consideration. Camera calibration is a key element for high DEM quality, which is extensively considered in photogrammetric software, whereas simpler models that solely estimate principle distance and radial distortion are usually implemented in the SfM tools originating from computer vision (Eltner and Schneider, 2015, James and Robson, 2012, Pierrot-Deseilligny and Clery, 2011). Fig. 6 also demonstrates that at same distances more extensive 3D reconstruction tools, implementing more complex camera models and several GCP integration possibilities (e.g. APERO, Pix4D, Agisoft PhotoScan) produce lower errors compared to tools considering basie camera models and no GCPs (e.g. Visual SfM, Bundler).

Image resolution

Image resolution is another factor influencing the final DEM quality. Especially, the absolute pixel size needs to be accounted for due to its relevance for the signal-to-noise ratio (SNR) because the larger the pixel the higher the amount of light that can be captured and hence a more distinct signal is measured. Resolution alone by means of pixel number gives no information about the actual metric sensor size. A large sensor with large pixels and a large amount of pixels provides better image quality due to reduced image noise than a small sensor with small pixels but the same amount of pixels. Thus, high image resolution defined by large pixel numbers and pixel sizes resolves in sufficient quality of images and thus DEMs (Micheletti et al., 2014, Eltner and Schneider, 2015).

However, in this study the reviewed investigations indicate no obvious influence of the pixel size at the DEM quality (Fig. 7). Mostly, cameras with middle sized sensors and corresponding pixel sizes around 5 μ m are used. In studies with pixel sizes larger 7 μ m an error ratio above 500 is observable. But else and a large range of error at different pixel sizes can be seen, which might be due to other error influences superimposing the impact of pixel size. Thus, more data is needed for significant conclusions is given.

To speed up processing, down-sampling of images is often performed causing interpolation of pixels and thus the reduction of image information, which can be the cause for underestimation of high relief changes, e.g., observed by Smith and Vericat (2015) or Nouwakpo et al. (2015). Interestingly, Prosdocimi et al. (2015) reveal that lower errors are possible with decreasing resolution due to an increase of error smoothing. Nevertheless, image data collection in the field should be done at highest realisable resolution and highest SNR to fully keep control over subsequent data processing, i.e. data smoothing should be performed under self-determined conditions at the desktop, which is especially important for studies of rough surfaces to allow for probate error statistics (e.g. Brasington et al., 2012).

Image network geometry

In regard to the geometry of the image network several parameters are important: number of images, image overlap, obliqueness, and convergence.

At least three images need to capture the area of interest, but for redundancy to decrease DEM error higher numbers are preferred (James and Robson, 2012). For instance, Piermattei et al. (2015) detect better qualities for a higher amount of images. However, the increase of images does not linearly increase the accuracy (Micheletti et al., 2014), and may ultimately lead to unnecessary increase in computation time. Generally, image number should be chosen depending on the size and complexity of the study reach (James and Robson, 2012); as high as possible but still keeping in mind acceptable processing time. The reviewed studies do not allow for distinct relation conclusions between 3D reconstruction performance and image number because the DEM error also interferes with other parameters, e.g. such as object complexity, image overlap or image convergence (Fig. 8).

High image overlap is relevant to finding homologous points within many images that cover the entire image space. Stumpf et al. (2014) show that higher overlap resolves in better results, even though ground sampling distance decreases due to a smaller focal length. Wide angle lenses, whose radial distortion is within the limits, should be chosen for data acquisition.
The reviewed studies reveal a large variety of applicable perspectives for DEM generation (Table 3). Most applications use images captured from the ground, which is the most flexible implementation of the SfM photogrammetry method. In regard to terrestrial or aerial perspective, Smith and Vericat (2015) state that aerial images should be preferred if plots reach sizes larger 100 m because at these distances obliqueness of images becomes too adverse. Stumpf et al. (2014) even mention a distinct value of the incidence angle of 30° to the captured surface above which data quality decreases significantly.

Furthermore, image network geometry has to be considered separately for convergent acquisitions schemes, common for terrestrial data collection, and for parallel-axes acquisition schemes, common for aerial data collection. The parallel-axes image configuration results in unfavourable error propagation due to unfavourable parameter correlation, which inherits the separation between DEM shape and radial distortion (James and Robson, 2014, Wu, 2014) resulting in a dome error that needs either GCP implementation or a well estimated camera model for error mitigation (James and Robson, 2014, Eltner and Schneider, 2015). However, GCP accuracy has to be sufficient or else the weight of GCP information during **BBABA** is too low to avoid unfavourable correlations, as shown by Dietrich (2016), where DEM dome error within a river reach could not be diminished even though GCPs were implemented into 3D reconstruction. If convergent images are utilised, the angle of convergence is important because the higher the angle the better the image network geometry and thus. Thereby, accuracy <u>increases</u> because sufficient image overlap is <u>possible</u> with larger bases between images is possible and thus less difficulties due to. Therefore, glancing ray intersections arise, which impede distinct depth assignment, are avoided. But simultaneously, convergence should not be so high that the imaged scene becomes too contradictory for successful image matching (Pierrot-Deseilligny and Clery, 2012, Stöcker et al, 2015).

Accuracy and distribution of homologues image points

The quality of DEMs reconstructed from overlapping images depends significantly on the image-matching performance (Grün, 2012). Image content and type, which cannot be enhanced substantially, are the primary factors controlling the success of image-matching (Grün, 2012). Image-matching is important for reconstruction of the image network geometry as well as the subsequent dense-matching.

On the one hand, it is relevant to find good initial matches (e.g. SIFT features are not as precise as least square matches with $\frac{1}{10}$ pixel size accuracies; Grün, 2012) to perform reliable 3D reconstruction and thus retrieve an accurate sparse point cloud because MVS approaches

for dense matching as well as optimization procedures for model refinement rely on this first point cloud. Thus, immanent errors will propagate along the different stages of SfM photogrammetry.

On the other hand, more obviously image-matching performance is important for dense reconstruction, when 3D information is calculated for almost every pixel. The accuracy of intersection during dense matching depends on the accuracy of the estimated camera orientations (Remondino et al., 2014). If the quality of the DEM is the primary focus, which is usually not the case for SfM algorithms originating from computer vision, the task of image-matching is still difficult (Grün, 2012). Nevertheless, newer approaches are emerging, though, which still need evaluation in respect of accuracy and reliability (Remondino et al., 2014). An internal quality control for image-matching is important for DEM assessment (Grün, 2012), but are mostly absent in tools for image-based 3D reconstruction<u>SfM photogrammetry</u>.

So far, many studies exist, which evaluate the quality of 3D reconstruction in geo-scientific applications. Nevertheless, considerations of dense-matching performance are still missing, especially in regard of rough topographies (Eltner and Schneider, 2015).

Surface texture

Texture and contrast of the area of interest is significant to identify suitable homologues image points. Low textured and contrasted surfaces result in a distinct decrease of image features, i.e. snow covered glaciers (Gómez-Gutiérrez et al., 2014) or sandy beaches (Mancini et al., 2013). Furthermore, vegetation cover complicates image matching performance due to its highly variable appearance from differing viewing angles (e.g. Castillo et al., 2012, Eltner et al., 2015) and possible movements during wind. Thus, in this study, <u>if possiblewhere present</u>, only studies of bare surfaces are reviewed for error assessment.

Illumination condition

Over- and under-exposure of images is another cause of error in the reconstructed point cloud, which cannot be significantly improved by utilising HDR images (Gómez-Gutiérrez et al., 2015). Well illuminated surfaces result in a high number of detected image features, which is demonstrated for coastal boulders under varying light conditions by Gienko and Terry (2014). Furthermore, Gómez-Gutiérrez et al. (2014) highlight the unfavourable influence of shadows because highest errors are measured in these regions; interestingly, these authors calculate the optimal time for image acquisition from the first DEM for multi-temporal data acquisition. Furthermore, the temporal length of image acquisition needs to be considered during sunny

conditions because with increasing duration shadow changes can decrease matching performance, i.e. with regard to the intended quality surveys lasting more than 30 minutes should be avoided (Bemis et al., 2014). Generally, overcast but bright days are most suitable for image capture to avoid strong shadows or glared surfaces (James and Robson, 2012).

GCP accuracy and distribution

GCPs are important inputs for data referencing and scaling. Photogrammetry always stresses the weight of good ground control for accurate DEM calculation, especially if one-staged **BBABA** is performed. In the common SfM workflow integration of GCPs is less demanding because they are only needed to transform the 3D-model from the arbitrary coordinate system, which is comparable to the photogrammetric two-staged **BBABA** processing. A minimum of three GCPs are necessary to account for model rotation, translation and scale. However, GCP redundancy, thus more points, has been shown to be preferable to increase accuracy (James and Robson, 2012). A high number of GCPs further ensures the consideration of checkpoints not included for the referencing, which are used as independent quality measure of the final DEM. More complex 3D reconstruction tools either expand the original 3D-Helmert-transformation by secondary refinement of the estimated interior and exterior camera geometry to account for non-linear errors (e.g. Agisoft PhotoScan) or integrate the ground control into the BBA (e.g. APERO).BA (e.g. APERO). For instance, Javernick et al. (2014) could reduce the height error to decimetre level by including GCPs in the model refinement.

Natural features over stable areas, which are explicitly identifiable, are an alternative for GCP distributions, although they usually lack strong contrast (as opposed to artificial GCPs) that would allow for automatic identification and sub-pixel accurate measurement (e.g. Eltner et al., 2013). Nevertheless, they can be suitable for multi-temporal change detection applications, where installation of artificial GCPs might not be possible (e.g. glacier surface reconstruction; Piermattei et al., 2015) or necessary as in some cases relative accuracy is preferred over absolute performance (e.g. observation of landslide movements, Turner et al., 2015).

GCP distribution needs to be even and adapted to the terrain resulting in more GCPs in areas with large changes in relief (Harwin and Lucieer, 2012) to cover different terrain types. Harwin and Lucieer (2012) state an optimal GCP distance between $\frac{1}{5}$ and $\frac{1}{10}$ of object distance for UAV applications. Furthermore, the GCPs should be distributed widely across the target area (Smith et al., 2015) and at the edge or outside the study areareach (James and Robson, 2012) to enclose the area of interest, because if the study reacharea is extended outside the GCP area, a significant increase of error is observable in that region (Smith et al., 2014, Javernick et al., 2014, Rippin et al., 2015 2014, Javernick et al., 2014, Rippin et al., 2015). If data acquisition is performed with parallel-axis UAV images and GCPs are implemented for model refinement, rules for GCP setup according to classical photogrammetry apply, i.e. dense GCP installation around the area of interest and height control points in specific distances as function of image number (more detail in e.g. Kraus, 2007).

The measurement of GCPs can be performed either within the point cloud or the images, preferring the latter because identification of distinct points in 3D point clouds of varying density can be less reliable (James and Robson, 2012, Harwin and Lucieer, 2012) compared to sub-pixel measurement in 2D images, where accuracy of GCP identification basically depends on image quality. Fig. 5<u>a</u> illustrates that only few studies measured GCPs in point clouds producing higher errors compared to other applications at the same distance.

5.32 Errors due to accuracy/precision assessment technique

Reference of superior accuracy

It is difficult to find a suitable reference for error assessment of SfM photogrammetry in geoscientific or geomorphologic applications due to the usually complex and rough nature of the studied surfaces. So far, either point based or area based measurements are carried out. On the one hand, point based methods (e.g. RTK GPS or total station) ensure superior accuracy but lack sufficient area coverage for precision statements of local deviations; on the other hand, area based (e.g. TLS) estimations are used, which provide enough data density but can lack of sufficient accuracy (Eltner and Schneider, 2015). Roughness is the least constrained error within point clouds (Lague et al., 2013) independent from the observation method. Thus, it is difficult to distinguish between method noises and actual signal of method differences, especially at scales where the reference method reaches its performance limit. For instance Tonkin et al. (2014) indicate that the quality of total station points is not necessarily superior on steep terrain.

Generally, 75 % of the investigations reveal a measured error that is <u>lower than</u>-20 times <u>higher than</u> the <u>reference</u> error. <u>of the reference</u>. But the median shows that <u>superiorthe</u> <u>superiority of the reference</u> accuracy <u>assessment</u> is actually significantly poorer; the measured error (measured error divided by reference accuracy) is merely twice the reference error (Fig. 4 <u>c</u>). The reviewed studies further indicate that the superior accuracy of the reference seems <u>scale dependentto depend on the camera-to-object distance</u> (Fig. 95 <u>b</u>). In shorter distances (below 50 m) most references reveal accuracies that are lower than one magnitude

superiority to the measured error. However, alternative reference methods are yet absent. Solely, for applications in further distances the references are sufficient. These findings are relevant for the interpretation of the <u>relative</u>error<u>ratio</u> because low ratios at small scale reaches might be due to the low performance of the reference rather than the actual 3D reconstruction quality but due to the reference noise lower errors are not detectable. Low <u>error</u><u>ratios</u><u>relative</u> errors are measured where the superior accuracy is also low (distance 5-50 m) and large ratios are given at distance where superior accuracy increases as well.

Type of deviation measurement

The reviewed studies use different approaches to measure the distance between the reference and the 3D reconstructed <u>DEMsurface</u>. Comparison are either performed in 2.5D (raster) or real 3D (point cloud). Lague et al. (2013) highlight that the application of raster inherits the disadvantage of data interpolation, especially relevant for rough surfaces or complex areas (e.g. undercuts as demonstrated for gullies by Frankl et al., 2015). In this context it is important to note that lower errors are measured for point-to-point distances rather than raster differencing (Smith and Vericat, 2015, Gómez-Guiérrez et al., 2014b).

Furthermore, within 3D evaluation different methods for deviation measurement exist. The point-to-point comparison is solely suitable for a preliminary error assessment because this method is prone to outliers and differing point densities. By point cloud interpolation alone (point-to-mesh), this issue is not solvable because there are still problems at very rough surfaces (Lague et al., 2013). Different solutions have been proposed: On the one hand, Abellan et al. (2009) proposed averaging the point cloud difference along the spatial dimension, which can also be extended to 4D (x, y, z, time; Kromer et al., 2015). On the other hand, Lague et al. (2013) proposed the M3C2 algorithm for point cloud comparison that considers the local roughness and further computes the statistical significance of detected changes. Stumpf et al. (2014) and Gómez-Gutiérrez et al. (2015) illustrated lower error measurements with M3C2 compared to point-to-point or point-to-mesh. Furthermore, Kromer et al. (2015) showed how the 4D filtering, when its implementation is feasible, allows to considerably increase the level of detection compared to M3C2other well-stablished techniques of comparison.

5.4<u>3</u> Standardised error assessment

To compare the achieved accuracies and precisions of different studies a standardised error assessment is necessary. In this review, besides actual measured error comparison, theoretical errors for the convergent image configuration are calculated (Eq. 1, Fig. 10) to compare if

applications in the field achieved photogrammetric accuracy (Luhman et al., 2014)., e.g. considering the theoretical error ratio. The calculation of the theoretical error for the convergent image acquisition schemes is possible, making some basic assumptions about the network geometry, i.e. the strength of image configuration equals 1 (as in James & Robson, 2012), the number of images equals 3 (as in James & Robson, 2012) and an image measurement error of 0.29 due to quantisation noise (as a result of continuous signal conversion to discrete pixel value). However, it is not possible to evaluate the theoretical error for parallel-axes case studies because information about the distance between subsequent images (base) is mostly missing. However, but essential to solve the equation and should not be assumed. Eltner and Schneider (2015) and Eltner et al. (2015) compare their results to parallel-axes theoretical error and could demonstrate that for soil surface measurement from low flying heights at least photogrammetric accuracy is possible.

(1)

Being:

 σ_c ... coordinate error,

q ... strength of image configuration (set to 1; according to James and Robson, 2012),
 k ... number of images (set to 3; according to James and Robson, 2012),

5

The results from James and Robson (2012), which show a less reliable performance of SfM than expected from photogrammetric estimation, can be confirmed by the reviewed studies. Image-based 3D reconstruction, considering SfM workflows, <u>performperforms</u> poorer than the theoretical error (Fig. <u>95c</u>). The measured error is always higher and on average 90 times worse than the theoretical error. Even for the smallest <u>theoretical error</u> ratio the actual error is 6 times higher. Furthermore, it seems that with increasing distance theoretical and measured errors converge slightly.

As demonstrated, diverse factors influence SfM photogrammetry performance and subsequent DEM error with different sensitivity. Generally, accurate and extensive data acquisition is necessary to minimise error significantly (Javernick et al., 2014). Independent reference sources, such as TLS, are not replaceable (James and Robson, 2012) due to their differing error properties (i.e. error reliability) compared to image-matching (Grün, 2012). Synergetic effects of SfM and classical photogrammetry should be used, i.e. benefiting from the high automation of SfM to retrieve initial estimates without any prior knowledge about the image

scene and acquisition configuration and adjacent reducing error by approved photogrammetric approaches, which are optimised for high accuracies.

The reviewed studies indicate the necessity of a standardised protocol for error assessment because the variety of studies inherit a variety of scales worked at, software used, GCP types measured, deviation measures applied, image network configurations implemented, cameras and platforms operated and reference utilised, making it very difficult to compare results with consistency. Relevant parameters for a standard protocol are suggested in Table 4<u>5</u>.

56 Perspectives and limitations

SfM photogrammetry has allowed capturing massive three-dimensional datasets by nonspecialists during the last five years, and it is highly expected that this technique will evolve during the forthcoming yearsdecade. Current studies are focusing intoon capturing the terrain's geometry with high precision, but several opportunities for using point clouds to improve our understanding, modelling and prediction of different earth surface processes still remain unexplored. In returnFor instance, the use of super-macro imagery in conventional SfM workflows is expected to be explored soon for investigating natural phenomena in a much higher level of detail. Nevertheless, some technical and operational aspects are still limiting our ability to acquire datasets over naturally complex outcrops. Sometechnological issues that need to be addressed include the progressive degradation of the data quality at longervery short distances, due to the effect of a limited depth of field on the; Up to our knowledge, the use of focus stacking for extending shallow depth of field of single images has not been explored yet. Some other technical and operational aspects are still limiting our ability to derive 3D point eloud quality clouds from digital imagery over naturally complex outcrops. Examples include the occurrence of biases and occlusions that can strongly influence the quality of the acquired datasets, and the useprogressive reduction of supermacro and super-zoom lenses for investigating unexplored natural phenomena, between others.the ground resolution (meter/pixel) at longer distances, which can be addressed using mobile platforms such as UAV systems. Eventually, SfM photogrammetry technique may become a mainstream procedure in geomorphological studies during the next decade, perspectives include efforts in cross-disciplinarity, process automatisation, data and code sharing, real time data acquisition and processing, unlocking the archives, etc., as follows:

6.1 Cross-disciplinarity

A great potential relies on adapting three dimensional methods originally developed for the treatment of 3D LiDAR data to investigate natural phenomena through SfM photogrammetry techniques. Applications, on 3D point cloud treatment dating back from the last decade, must will soon be integrated into SfM photogrammetry post-processing; Examples include: geomorphological investigations in high mountain areas (Milan et al., 2007), geological mapping (Buckley et al., 2008; Franceschi et al. 2009), soil erosion studies (Eltner and Baumgart, 2015), investigation of fluvial systems (Heritage and Hetherington, 2007, Cavalli et al., 2008; Brasington et al., 2012), and mass wasting phenomena (Lim et al., 2005, Oppikofer et al. 2009, Abellan et al., 2010).

More specifically, several<u>Some other</u> data treatment techniques <u>that</u> have been developed during the last decade <u>for different situations</u>, <u>whichand that</u> will <u>need to</u> be known, adapted and enriched by the growing SfM photogrammetry community; <u>Examples</u> include: automatic lithological segmentation according to the intensity signature (Humair et al., 2015), integration of ground based LiDAR with thermal/hyperspectral imaging for lithological discrimination (Kääb, 2008, Hartzell et al., 2014), extraction of the structural settings on a given outcrop (Jaboyedoff et al., 2007, Sturzenegger and Stead, 2009, Gigli and Casagli, 2011, Riquelme et al., 2014), <u>of the</u>, discontinuity spacing/persistence/waviness (Fekete et al. 2010, Khoshelham et al., 2011, Pollyea and Fairley, 2011),. Concerning 4D data treatment for investigating changes on natural slope, some lessons learned may be adapted from the bi- and three-dimensional tracking of mass movements (Teza et al., 2007, Monserrat and Crosetto 2008), investigation of progressive failures (Royan et al., 2015, Kromer et al., 2015), and <u>from the</u> usage of mobile systems (Lato et al., 2009, Michoud et al., 2015).

6.2 Process-automatisation

Handling huge databases is an important issue and although fully automatic techniques may not be necessary in some applications, a series of tedious and manual processes are still required for data treatment.

6.3 Data and code sharing

<u>Open data in geomorphometric studies using point clouds is also needed.</u> The development of open-source software for handling huge 3D datasets such as CloudCompare (Girardeau-Montaut, 2015) has considerably boosted geomorphologicalgeomorphometric studies using 3D point clouds. Nevertheless, appart from the above mentioned case, sharing the source code

or the RAW data of specific applications for investigating earth surface processes is still scarce.

6.3 Data and code sharing

Open datanot well stablished in geomorphological studies using point clouds is also needed. Again,our discipline. A series of freely available databases exist for LiDAR datasets (openTopography.org, rockbench.com, 3D-landslide.com). But up to the knowledge of these authors, there is no specific Git-Hub cluster or website dedicated to the maintaining and development of open-access software in geosciences

6.4 Unlocking the archive

The appraisal of digital photography and the exponential increase of data storage capabilities have enabled the massive archive of optical images around the world. Accessing to such quantity of information could provide unexpected opportunities for the four dimensional research of geomorphological processes using SfM photogrammetry workflows. Except for some open repositories (e.g. Flickr, Google street view) the possibility to access the massive optical data is still scarce. In addition, accessing to such databases may become a challenging task due to data interchangeability issues. A considerable effort may be necessary for creating such database with homogeneous data formats and descriptors (type of phenomenon, temporal resolution, pixel size, accuracy, distance to object, existence of GCPs, etc.) during the forthcoming years.

A first valuable approach to use data from online imagery was presented by Martin-Brualla et al. (2015), who pave the way for further research in a new field of 3D surface analysis (i.e. time-lapse). Other possible applications might unlock the archive of <u>ancient</u> airborne, helicopter-based or terrestrial imaginary, ranging from the estimation of coastal retreat rates, the observation of the evolution of natural hazards to the monitoring of glacier fronts, and further.

6.5 Real time data acquisition

Rapid developments in automatisation (soft- and hardware wise) allow for in situ data acquisition and its immediate transfer to processing and analysing institutions. Thus, extreme events are recognisable during their occurrence and authorities or rescue teams can be informed in real-time. In this context SfM photogrammetry could help to detect and quantify rapid volume changes of e.g. glacier fronts, pro-glacial lakes, rock failures and ephemeral rivers.

Furthermore, real-time crowd sourcing offers an entirely new dimension of data acquisition. Due to the high connectivity of the public through smartphones, various possibilities arise to share data (Johnson-Roberson et al., 2015). An already implemented example is real-time traffic information. Jackson and Magro (2015) name further options. Crowd sourced imagery can largely expand possibilities to 3D information.

6.6 Time-lapse photography

A limited frequency of data acquisition increases the likelihood of superimposition and coalescence of geomorphological processes (Abellan et al., 2014). Since time-lapse SfM photogrammetry data acquisition has remained so far unexplored, a great prospect is expected on this topic during the coming years. To date solely James and Robson (2014b) demonstrated its potential by monitoring a lava flow at minute intervals for 37 minutes. One reason why time-lapse SfM photogrammetry remains rather untouched in geosciences lies in the complex nature of producing continuous data sets.

Besides the need for an adequate research site (frequent morphodynamic activity), other aspects have to be taken into account: an automatic camera setup is required with selfcontained energy supply (either via insolation or wind), adequate storage and appropriate choice of viewing angles onto the area of interest. Furthermore, cameras need to comprise sufficient image overlap and have to be synchronised. Ground control is required and an automatic pipeline for large data treatment should be developed.

New algorithms are necessary to deal with massive point cloud databases. Thus, innovative four dimensional approaches have to be developed to take advantage of the information contained in real-time and/or time-lapse monitoring. Combining these datasets with climatic information can improve the modelling of geomorphological processes.

6.7 Automatic UAV surveying (no human controller)

Unmanned airborne vehicles already show a large degree of automatisation as they follow flight paths and acquire data autonomously. Human control is not required except for launching of the multi-copter or fixed wing system. Automatic landing is already provided by several systems. In near future a fully automatic UAV installation could comprise the following: repeated survey of an area of interest, landing and charging at a base station, data link for local storage or satellite based data transfer, and safety mechanism for preventing liftoff during inappropriate weather conditions. However, a large limitation for such realisation lies in legal restrictions because national authorities commonly request for visual contact to the UAV in case of failure. But in remote areas installation <u>of an automatic system</u> could already be allowed by regulation authorities.

6 Conclusion

6.8 Direct geo-referencing

The use of GCPs is very time-consuming in the current SfM workflow. At first, field efforts are high to install and measure the GCPs during data acquisition. Afterwards, again much time and labour is required during post-processing in order to identify the GCPs in the images, although some progress is made regarding to automatic GCP identification, e.g. by the exploitation of templates (Chen et al., 2000). The efficiency of geo-referencing can be increased significantly applying direct geo-referencing. Thus, the location and position of the camera is measured in real time and synchronised to the image capture by an on-board GPS receiver and IMU (inertial measurement unit) recording camera tilts. This applies to UAV systems as well as terrestrial data acquisition, e.g. by smartphones (Masiero et al., 2014). Exploiting direct geo-referencing can reduce usage of GCPs to a minimum or even replace it, which is already demonstrated by Nolan et al. (2015), who generated DEMs with spatial extents of up to 40 km² and a geo-location accuracy of \pm 30 cm.

The technique can be very advantageous when it comes to monitoring areas with great spatial extents or inaccessible research sites. However, further development is necessary, thereby focusing on light-weighted but precise GPS receivers and IMU systems; on UAVs due to their limited payload and for hand-held devices due to their feasibility (e.g. Eling et al., 2015).

7 Conclusions

This review has shown the versatility and flexibility of the evolvingrecently established method SfM photogrammetry, which is recapitulated in Fig. 11. Due to its beneficial qualities, a wide community of geoscientists starts to implement 3D reconstruction based on images within a variety of studies. Summing up the publications, there are no considerable disadvantages mentioned (e.g. accuracy wise) compared to other methods that cannot be counteracted by placement of GCPs, camera calibration or a high image number. Frontiers in geomorphometry have been expanded once more, as limits of other surveying techniques such

as restricted mobility, isolated area of application and high costs are overcome by the SfM photogrammetry. Its major advantages lie in easy-to-handle and cost-efficient digital cameras as well as non-commercial software solutions.

Performance analysis revealed the suitability of SfM photogrammetry at a large range of scales in regard to case study specific accuracy necessities. SfM photogrammetry is already becoming an essential tool for digital surface mapping. It is employable in a fully automatic manner but individual adjustments can be conducted to account for each specific case study constrain and accuracy requirement in regard to the intended application. Due to the possibility of different degrees of process interaction, non-experts can utilise the method depending on their discretion.

While research of the last years mainly focussed on testing the applicability of SfM photogrammetry in various geo-scientific applications, recent studies try to pave the way for future usages and develop new tools, setups or algorithms. Performance analysis revealed the suitability of SfM photogrammetry at a large range of scales in regard to case study specific accuracy necessities. However, different factors influencing final DEM quality still need to be addressed. This should be performed under strict experimental (laboratory) designs because complex morphologies, typical in earth surface observations, impede accuracy assessment due to missing superior reference. Thus, independent references and GCPs are still needed in SfM photogrammetry for reliable estimation of the quality of each 3D reconstructed surface.

Fast and facilestraightforward generation of DEMDEMs using freely available tools produces new challenges. The exploitation of the entire information of the SfM photogrammetry output (3D point cloud or mesh instead of 2.5D raster) will become a significant issuechallenge in future studies of high resolution topography (Passalacqua et al., 2015), which has to be even extended to 4D when additionally considering investigating the evolution along time. Thus, especially comprehensive end user software needs further progress in these aspects.

Nevertheless, SfM photogrammetry is already becoming an essential tool for digital surface mapping. It is employable in a fully automatic manner but individual adjustments can be conducted to account for each specific case study constrain and accuracy requirement in regard to the intended application. Due to the possibility of different degrees of process interaction, non-experts can utilise the method depending on their discretion.

1 Appendix A:

ID	Author	Voor	Application	Softwara	Doronactiva	Distance	Seele*	Divol	Imaga	Comployity	Magguramant	Polotivo	rafara
ID	Autioi	real	Application	Soltwale	Perspective		Scale.	Pixel	Image	Complexity	wieasurement	Relative	referen
						[m]	[m]	size	number	of SIM tool	error [mm]	error	superi
								[µm]					
1	Castillo et	2012	gully erosion	Bundler +	terrestrial	7	7	5.2	191	basic	20	350	-
	al.			PMVS2									
2	Castillo et	2014	ephemeral gully	Bundler +	terrestrial	6	25	5.2	515	basic	22	273	11
	al.		erosion	PMVS2									
3	Castillo et	2015	gully erosion	SF3M	terrestrial	10	350	1.5	3095	basic	69	145	3.45
	al.												
4	Dietrich	2016	riverscape	PhotoScan	helicopter	200	10000	4.3	1483	complex	730	274	-
			mapping		-					-			
5	Eltner et al.	2015	soil erosion	Pix4D	UAV	10	30	2.0,	100	complex	5,6	2000,	-
								5.0		-		1667	
6	Eltner and	2015	soil roughness	VisualSfM +	UAV	12	15	5.0	13	basic,	8.1 - 9.8	1224 -	-
	Schneider		8	PMVS2.						complex		1481	
				PhotoScan.						ľ			
				Pix4D. APERO									
				+ MicMac.									
				Rundler +									
				PMVS2									
7	Favalli at	2012	goologiaal	$\frac{1}{101} \frac{1}{100} \frac{1}{100} \frac{1}{100}$	tonnostnial	1	0.1	5 2	20 67	hasia	02 20	267	
1	ravalli et	2012	geological		terrestrial	1	U.I -	J.4	30-0/	Dasic	0.3 - 3.8	JU/ -	-
	a I.		outcrops,	PINI V 82			0.3					5555	
			volcanic bomb,										

Table summarisesSummary of information about reviewed studies used for application evaluation and performance assessment of SfM photogrammetry. Variables are explained in chapter 5.

2 3

8	Fonstad et al.	2013	stalagmite bedrock channel and floodplain	Photosynth (Bundler implementation)	terrestrial	40	200	1.7	304	basic	250	160	2
9	Frankl et al.	2015	gully measurement	PhotoScan	terrestrial	2	10	5.2	180 - 235	complex	17 - 190	11 - 147	0 - 4
10	Genchi et al.	2015	bioerosion pattern	VisualSfM + PMVS2	UAV	20	100	1.5	400	basic	35	571	-
11	Gómez- Gutiérrez et al.	2014	gully headcut	123D catch	terrestrial	9.3 - 10.5	10	4.3	41 - 93	basic	12 - 32	291 - 792	-
12	Gómez- Gutiérrez et al.	2014	rock glacier	123D catch	terrestrial	300	130	8.2	6	basic	430	698	72
13	Gómez- Gutiérrez et al.	2015	rock glacier	123D catch, PhotoScan	terrestrial	300	130	8.2	9	basic, complex	84 - 1029	-	-
14	Immerzeel et al.	2014	dynamic of debris coverd glacial tongue	PhotoScan	UAV	300	3500	1.3	284, 307	complex	330	909	-
15	James and Robson	2012	volcanic bomb, summit crater, coastal cliff	Bundler + PMVS2	terrestrial, UAV	0.7 - 1000	0.1 - 1600	5.2, 7.4	133 - 210	basic	1000 - 2333	0 - 62	1 - 12
16	Javernick et al.	2014	braided river	PhotoScan	helicopter	700	1500	-	147	complex	170	4118	3
17	Johnson et al.	2014	alluvial fan, earthquake scarp	PhotoScan	UAV	50, 60	300, 1000	4.8	233. 450	complex	130 - 410	122 - 385	-

18	Kaiser et al.	2014	gully and rill erosion	PhotoScan	terrestrial	5	10	6.4	-	complex	73 - 141	35 - 68	-
19	Leon et al.	2015	coral reef roughness	PhotoScan	terrestrial (marine)	1.5	250	1.5	1370	complex	0.6	2500	-
20	Mancini et al.	2013	fore dune	PhotoScan	UAV	40	200	4.3	550	complex	110 - 190	211 - 364	4
21	Micheletti et al.	2014	river bank, alluvial fan	123D Catch	terrestrial	10, 345	10, 300	4.8, 1.8	13	complex	16.8 - 526.3	327 - 595	-
22	Nadal- Romero et al.	2015	badland erosion	PhotoScan	terrestrial	50, 125	50, 100	5.5	15, 17	complex	14 - 33	2500 - 4032	1 - 2
23	Nouwakpo et al.	2015	microtopography erosion plots	PhotoScan	terrestrial	2	6	6.4	25	complex	5	400	-
24	Ouédraogo et al.	2014	agricultural watershed	Apero + MicMac, PhotoScan	UAV	100	200	2.0	760	complex	90, 139	1111, 719	-
25	Piermattei et al.	2015	debris covered glacier monitoring	PhotoScan	terrestrial	100	350	4.8, 6.3	35, 47	complex	300, 130	333, 769	2, 1
26	Prosdocimi et al.	2015	channel bank erosion	PhotoScan	terrestrial	7	30	1.4 - 6.3	60	complex	57 - 78	90 - 123	1
27	Rippin et al.	2015	supra-glacial hydrology	PhotoScan	UAV	121	2000	2.2	423	complex	400	303	-
28	Ruzic et al.	2014	coastal cliff	Autodesk ReCap	terrestrial	15	50	2.0	250	basic	70	214	1
29	Smith et al.	2014	post-flash flood evaluation	PhotoScan	terrestrial	50	150	1.7	-	complex	135	370	14
30	Smith and	2015	badland changes	PhotoScan	terrestrial,	5 - 250	20 -	1.7,	30 -	complex	12.8 - 445	132 - 974	2 - 89

	Vorioot		at different		TIAN		1000	5.5	527				
	vericat				UAV,		1000	5.5	521				
31	C • • • •	0014	scales		AutoGiro	0.6	2		7 00			222	250
31	Snapır et al.	2014	roughness of soil surface	SIMTOOIkit	terrestrial	0.6	3	4.3	700	basic	2.7	222	270
32	Stumpf et al.	2014	landslide scarp	VisualSfM + CMVS, APERO + MicMac	terrestrial	50	750	8.5	88 - 401	basic, complex	27 - 232	667 - 1852	1 - 3
33	Tamminga et al.	2015	change detection after extreme flood event	EnsoMOSAIC UAV	UAV	100	200	1.3	310	complex	47	2128	2
34	Tonkin et al.	2014	moraine-mound topography	PhotoScan	UAV	100	500	4.3	543	complex	517	193	-
35	Turner et al.	2015	landslide change detection	PhotoScan	UAV	40	125	4.3	62 - 415	complex	31 - 90	444 - 1290	1 - 3
36	Westoby et al.	2012	coastal cliff	SfMToolkit	terrestrial	15	300	4.3	889	basic	500	100	-
37	Westoby et al.	2014	moraine dam, alluvial debris fan	SfMToolkit3	terrestrial	500	500	4.3	1002, 1054	basic	814, 85	614, 1176	2, 43
38	Woodget et al.	2015	fluvial topography	PhotoScan	UAV	26 - 28	50, 100	2.0	32 - 64	complex	19 - 203	138 - 1421	-
39	Zarco- Tejada et al.	2014	tree height estimation	Pix4D	UAV	200	1000	4.3	1409	complex	350	571	23
40	Bemis et al.	2014	structural geology	PhotoScan	UAV, terrestrial	-	-	-	-	-	-	-	-
41	Bendig et al.	2013	crop growth	PhotoScan	UAV	30	7	-	-	-	-	-	-
42	Bini et al.	2014	coast	Bundler	terrestrial	-	-	-	-	-	-	-	-

			erosion/abrasion										
43	Bretar et al.	2013	(volcanic) surface	APERO +	terrestrial	1.5	5.9 -	-	-	-	-	-	-
			roughness	MicMac			24.6						
44	Brothelande	2015	post-caldera	PhotoScan	aircraft	150	6000	8.2	7000	-	3100	48	62
	et al.		resurgence										
45	Burns et al.	2015	coral reef	Photoscan	terrestrial	2	28	-	-	-	-	-	-
					(marine)								
46	Clapuyt et	2015	slope morphology	VisualSFM	UAV	50	100	-	-	-	-	-	-
	al.												
47	Dall'Asta et	2015	rock glacier	APERO +	UAV	150		-	-	-	-	-	-
	al.		monitoring	MicMac,									
				Photoscan									
48	Dandois and	2013	vegetation	Photoscan	UAV	130	250	-	-	-	-	-	-
	Ellis		mapping										
49	Fernández et	2015	landslide	Photoscan	UAV	90	250	-	-	-	-	-	-
	al.												
50	Gienko and	2014	coastal boulders	Photoscan	terrestrial	3	2.5	-	-	-	-	-	-
	Terry												
51	Fugazza et	2015	glacier mapping	Menci APS	UAV	250	500	-	-	-	-	-	-
	al.												
52	Gomez	2014	volcano	Photoscan	aircraft	-	10000	-	-	-	-	-	-
			morphology										
53	Harwin and	2012	coastal erosion	Bundler +	UAV	120	100	-	1	-	-	-	-
	Lucieer			PMVS2									
54	James and	2012	volcanic dome	Bundler	aircraft	505 -	250	-	-	-	-	-	-
	Varley		control	Photogrammetry		2420							
				package									
55	Kaiser et al.	2015	soil hydraulic	PhotoScan	terrestrial	0.5	1	-	-	-	-	-	-

			roughness										
56	Lucieer et	2013	landslide	PhotoScan	UAV	40	125	-	-	-	-	-	-
	al.												
57	Lucieer et	2014	antartic moss beds	PhotoScan	UAV	50	64	-	-	-	-	-	-
	al.												
58	Meesuk et	2014	Urban flooding	VisualSfM	terrestrial	-	-	-	-	-	-	-	-
	al.												
59	Morgenroth	2014	tree structure	Photoscan	terrestrial	5	5	-	-	-	-	-	-
	and Gomez												
60	Nouwakpo	2014	soil	Photoscan	terrestrial	3.1	10	-	-	-	-	-	-
	et al.		microtopography										
61	Stöcker et	2015	gully erosion	APERO +	terrestrial	2 + 15	35	-	-	-	-	-	-
	al.			MicMac	+ UAV								
62	Ryan et al.	2015	glacier drainage	Photoscan	UAV	500	5000	-	-	-	-	-	-
			observation										
63	Torres-	2015	tree plantation	Photoscan	UAV	50, 100	-	-	-	-	-	-	-
	Sánchez et												
	al.												
64	Turner et al.	2015	landslide	Bundler +	UAV	50	-	-	-	-	-	-	-
			monitoring	PMVS2									
65	Vasuki et al.	2014	structural geology	Bundler +	UAV	30 - 40	100	-	-	-	-	-	-
				PMVS2									

1

2 These studies are considered for performance analysis.

3 For most authors not all camera parameters are given. Hence, camera parameters are retrieved from dpreview.com (or similar sources).

4 * If scale or distance is not given, they are estimated from study area display.

1 Appendix B:

2 Table summarises non-commercial software tools beneficial for SfM photogrammetry processing and post-processing.

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Table 1. Nomenclature and brief definitions of image-based 3D reconstruction related terms

Table 1. Nomenciatu	ire and orier definitions of image-based 3D reconstruction related terms											
Image-based 3D	recording of the three-dimensional shape of an object from											
reconstruction	overlapping images from different perspectives											
Computer Vision	algorithmic efforts to imitate human vision with focus on											
	automation, amongst others, to reconstruct 3D scenes with methods											
	of image processing and image understanding											
Structure from	fully automatic reconstruction of 3D scenes from 2D images and											
Motion (SfM)	simultaneous retrieval of the corresponding camera geometry in an											
	arbitrary coordinate system											
Photogrammetry	algorithmic efforts to determine 3D model coordinates and camera											
	geometry focussing on accuracy and precise measurement in											
	images											
SfM	fully automatic reconstruction of 3D scenes from 2D images and											
photogrammetry	camera geometry with option to set parameters for											
	(photogrammetric) optimisation of accuracy and precision											
Dense matching	increase of resolution of point clouds that model 3D scenes by											
	pixel- or patch-wise matching in images of known intrinsic and											
	extrinsic parameters											
Stereo matching	reconstruction of object point through matching (in image space,											
	Remondino et al., 2014) between two overlapping images											
ulti-View-Stereo	reconstruction of object point through matching (in object space,											
(MVS) matching	Remondino et al., 2014) from multiple overlapping images											
Extrinsic	exterior camera geometry comprising position (three shifts) and											
parameters	orientation (three rotations) of the camera projection centre											
Intrinsic parameters	interior camera geometry comprising principle distance (distance											
	between projection centre and image sensor), principle point											
	(intersection of perpendicular from projection centre onto image											
	plane) and distortion parameters (e.g. radial distortion)											
Bundle adjustment	least-square optimisation to simultaneously solve for extrinsic (and											
(BA)	intrinsic) parameters of all images; the term bundle correlates to											
	rays that derive from 3D points, converge in corresponding											
	projection centres and intersect with image sensor											
Camera self-	intrinsic camera parameters are included as additional unknowns											
calibration	into BA to solve for interior camera geometry											
Ground Control	in images clearly distinguishable point whose object coordinates are											
Point (GCP)	known to geo-reference surface model											
Digital Elevation	3D description of the surface in either raster (grid) or vector (mesh)											
Model (DEM)	format											
Point cloud	quantity of points of 3D coordinates describing the surface within											
	arbitrary or geo-referenced coordinate system, additional											
	information such as normals or colours possible											
Software		Bundler	PMVS2	Apero+ MicMac	SfMToolkit	Meshlab	Cloud Compare	Sfm_georef	VisualSFM	SF3M	Photosynth	123D Catch
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Туре		Open Source	Open Source	Open Source	Open Source	Open Source	Open Source	Freely- available	Freely- available	Freely- available	Free web service	Free web service
Website		http://www. cs.cornell.e du/~snavely /bundler	http://www. di.ens.fr/pm vs	http://logici els.ign.fr/? Micmac	http://www. visual- experiments .com/demos /sfmtoolkit	http://meshl ab.sourcefor ge.net	http://www. danielgm.ne t/cc	http://www. lancaster.ac. uk/staff/jam esm/softwar e/sfm_geore f.htm	http://ccwu. me/vsfm	http://sf3ma pp.csic.es	https://phot osynth.net	http://www. 123dapp.co m/catch
Operative system		Linux Windows	Linux Windows	Linux Mac Windows	Windows	Mac Windows	Linux Mac Windows	Windows	Linux Mac Windows	Windows	Windows	Windows Mac
	Camera calibration			X								
Functionalites	Bundle adjustment	X			X				X	X	X	X
	Bundle adjustment with GCPs			X								
	Sparse 3D re- construction	X		x	x				x	x	x	X
	Geo- referencing			X				X	X	X		
	Dense 3D re- construction		X	X					X	X		X
	Post- processing			x						x		

Table 2: Summary of non-commercial software tools beneficial for SfM photogrammetry processing and post-processing.

	Advanced				
	cloud	X	Х		
	processing				
1					

Table 3: Key developments of SfM photogrammetry towards a standard tool in geomorphometry

key developments	authors					
method introduction	James & Robson (2012), Westoby et al. (2012), Fonstad et al.					
	(2013)					
evaluation of accuracy potential	James & Robson (2012), Westoby et al. (2012), Castillo et al.					
	(2012)					
SfM with terrestrial images	James & Robson (2012), Westoby et al. (2012), Castillo et al.					
	(2012)					
SfM with UAV images	Harwin & Lucieer (2012)					
application with mm resolution	Bretar et al. (2013), Snapir et al. (2014)					
application covering km ²	Immerzeel et al. (2014)					
mitigation of systematic errors (i.e. dome)	James & Robson (2014a), Eltner & Schneider (2015)					
influence of image network geometry	Stumpf et al. (2014), Micheletti et al. (2014), Piermattei et al.					
	(2015)					
usage of Smartphone for data acquisition	Micheletti et al. (2014)					
time-lapse implementation	James & Robson (2014b)					
influence of scale	Smith & Vericat (2015)					
comparing tools and cameras	Eltner & Schneider (2015)					
synergetic usage of terrestrial and aerial images	Stöcker et al. (2015)					
sub-merged topography	Woodget et al. (2015)					
under water application	Leon et al. (2015)					
reuse of historical images	Gomez et al. (2015)					

Table 2.

Торіс	2012	2013	2014	2015	2016	ID	Total number of publications on the respective topic
Soil science/erosion	1	-	5	9	-	1, 2, 3, 5, 6, 9, 11, 18, 22, 23, 30, 31, 55, 60, 61	15
Volcanology	3	1	1	1	-	7, 15, 43, 44, 52, 54	6
Glaciology	-	-	4	6	-	12, 13, 14, 25, 27, 34, 37, 47, 51, 62	10
Mass movements	-	1	1	3	-	32, 35, 49, 56, 64	5
Fluvial morphology	-	1	5	3	1	4, 8, 16, 17, 21, 26, 29, 33, 37, 38	10
Coastal morphology	3	1	3	-	-	15, 20, 28, 36, 42, 50, 53	7
Others	1	2	8	5	-	7, 10, 17, 19, 24, 39, 40, 41, 45, 46, 48, 57, 58, 59, 63, 65	16
Topics (publications)	8 (6)	6 (6)	27 (25)	27 (27)	1(1)		69 (65)

<u>Table 4.</u> Overview of the publication history divided in the main topics from 2012 until editorial deadline in <u>SepNov</u>. 2015. Several publications examined more than one topic resulting in a larger number of topics (number without brackets) than actual publications (number in brackets). in last row). IDs refer to the table in appendix A1.

Table 3. Different perspectives/platforms used for image<u>5</u>: Data acquisition of all 62 reviewed studies.Table 4: Parameters of a standard protocol for and error assessment protocol for SfM photogrammetry; independent from individual study design.

in the field:									
S	study area extent			10	GCP measurement (total station, GPS,)				
pecific	sensor to surface distance			contro cifics	GCP description				
arget s	ground sampling distance		round	round	GCP number				
ц.	target complexity			60	GCP accuracy				
	camera name			S	illumination condition				
	camera type (SLR, CSC,)			pecific	image number				
cifics	lens type (zoom - fixed)			ition s]	image overlap				
ıra spe	sensor resolution			acquisi	base (distance between images)				
came	sensor size			mage a	network configuration (conv parallel-axis)				
	pixel size			Ţ	perspective (aerial - terrestrial)				
	focal length			notes					
at the of	fice:		1 6						
ssing S	SfM tool			ţ	registration residual				
proce	GCP integration (1-/2-staged)			y assessmen	reference type (LiDAR, RTK pts,)				
data S	output data type				reference error				
SO	relative error			ccurac	error measure (M3C2, raster difference,)				
or rati	reference superiority			ŋ	statistical value (RMSE, std dev,)				
err	theoretical error ratio			notes					

Figure captions

Figure 1. Exemplary workflow of image-based 3D reconstruction: a) illustration of a micro-plot (1 m²), b) matched-image pair with homologous points, c) reconstructed image network geometry with sparse point cloud, d) dense-matched point cloud, e) meshed DEM of micro-plot

Figure 1: Schematic illustration of the versatility of SfM photogrammetry.

Figure 2. Map of the research sites of all studies of this review.

Figure 3. Variety of softwareSfM photogrammetry tools used in the 6265 reviewed studies.

Figure 4. Boxplots summarizing statistics: a) of the scale, of the study reaches (N: 56; ID 1-3 and 5-39 in Appendix A), b) the relative error ratio (calculated in regard to distance and measured error, N: 54; ID 1-3, 5-12 and distance)14-39 in Appendix A), and superiorc) the reference ratio superiority (calculated in regard to measured error and reference error, N: 33; ID 1-30 and 32-39 in Appendix A) of reviewed studies.

Figure 5. Relationship between Performance of several error parameters in regard to the camera to surface distance.a) Characteristics of measured error, error ratio and distance.and relative error (N: 54; ID 1-3, 5-12 and 14-39 in Appendix A). For grey coloured points GCPs are measured in point cloud (in total 9 times corresponding to the studies: ID 8, 11, 12, 28, 36, 37 in Appendix A) and for white points GCPs are measured in images (corresponding to the remaining studies) for model transformation.

Figure 6. Image-based 3D reconstruction performance of software considering basic and complex camera models.

Figure 7. Influence of pixel size (and thus SNR) at the error ratio.

Figure 8. No distinct relation between error and amount of images detectable. Different scales are considered with point grey scales.

Figure 9.<u>b</u>) Superiority of the reference data. Superior reference ratio (N: 33), which is calculated as ratio between measured error and accuracyerror of the reference. Area based and point based (ID 5-7, 12, 15, 17, 22, 25, 26, 30 and 32 in Appendix A) and point based (ID 2, 3, 8, 9, 20, 24, 28-30, 33, 35 and 37 in Appendix A) reference measurements are distinguished.

Figure 10. Ratio of the <u>c</u>) Theoretical error ratio, considering the theoretical and measured error displayed against distance, to illustrate image-based 3D reconstructionSfM photogrammetry performance in field applications- (N: 23; ID 1-3, 8, 10-12, 15, 21, 22, 25, 26, 28-30 and 32 in Appendix A).

Figure 11: Schematic illustration of the versatility of SfM photogrammetry.